NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

A SYSTEMS ENGINEERING APPROACH IN PROVIDING AIR DEFENSE SUPPORT TO GROUND COMBAT VEHICLE MANEUVER FORCES

by

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March 2015

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** March 2015	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE A SYSTEMS ENGINEERING APPROACH IN PROVIDING AIR DEFENSE SUPPORT TO GROUND COMBAT VEHICLE MANEUVER FORCES			**5. FUNDING NUMBERS**
6. AUTHOR(S) Jianhao Ng			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

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There is an identified capability gap for mobile air defense in the U.S. Armed Forces in operating environments with terrain. Using a systems engineering approach, this study looks into the stakeholder needs and functions required to fulfill this capability gap. In defining the physical architecture, there are many factors that could affect the design of a mobile air defense system. Physically addressing all permutations of the attributes would be onerous and inefficient. For an identified concept of operations, a design of experiment was used to expedite the assessment process by identifying significant design factors.

The objective is to provide program managers with a mobile air defense system assessment framework. The framework currently utilizes indicative responses in lieu of inaccessible combat data. When used in conjunction with real data, the framework would help make the acquisition process more efficient.

14. SUBJECT TERMS			**15. NUMBER OF PAGES**
systems engineering, mobile air defense, ground combat vehicle, design of experiment			123
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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A SYSTEMS ENGINEERING APPROACH IN PROVIDING AIR DEFENSE SUPPORT TO GROUND COMBAT VEHICLE MANEUVER FORCES

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

ATGM	anti-tank guided missile
BFV	Bradley fighting vehicle
CAS	close air support
CLAWS	complementary low altitude weapon system
CLOS	command line of sight
DIVAD	division air defense
DOD	Department of Defense
DODAF	Department of Defense Architecture Framework
DOE	design of experiment
EMMI	energy, mass, material wealth, information
FNF	fire and forget
GCV	ground combat vehicles
HAWK	homing all the way kill
HMMWV	high mobility multi-purpose wheeled vehicle
HIMAD	high-to-medium air defense
IFF	identification of friend or foe
INCOSE	International Council on Systems Engineering
JCA	Joint Capability Area
NATO	North Atlantic Treaty Organization
OA	operational activities
ODS	Operation Desert Storm
MAD	mobile air defense
MANPADS	man-portable air defense system
MEADS	medium extended air defense system
MOE	measure of effectiveness
MOM	measure of merit
MOP	measure of performance
MUA	man-portable air defense system-under-armor
NPS	Naval Postgraduate School
PATRIOT	phased array tracking radar to intercept on target

RAM	rocket, artillery, mortar
RPG	rocket propelled grenade
SAM	surface to air missile
SEAD	suppression of enemy air defense
SEBoK	Systems Engineering body of knowledge
SHORAD	short-range air defense
SLAMRAAM	surface launched advanced medium range air-to-air missile
SME	subject matter expert
SOS	system of systems
UAV	unmanned aerial vehicle
UCAV	unmanned combat aerial vehicle
VSHORAD	very-short-range air defense

EXECUTIVE SUMMARY

A review of Joint Capability Areas reveals the capability need for maneuver forces remain relevant. Ground combat vehicles are susceptible to aerial threats. During maneuver, a formation may be in unfamiliar territory, and without established local air defense support. Based on current systems in the U.S. Armed Forces, there is an identified capability gap for mobile air defense especially in an operating environment with terrain. Acquisition of a mobile air defense system may be required to increase the survivability of ground combat vehicles during movement in an operating environment with terrain. Acquisition of a weapon system is a complex and iterative task. This study adopts a systems engineering approach in developing an assessment framework to aid program managers in the acquisition of a mobile air defense system.

The systems engineering process is a systematic and holistic method of generating the required functions and components to implement the capability needs and operational activities needed by stakeholders. The method used in this systems engineering acquisition process is to first, define the problem; second, conduct stakeholder analysis; third, conduct operational analysis; fourth, conduct functional analysis; and fifth, generate the physical architecture. The result of this method that iterates between these five tasks is an interlinked characterization of the system concept for delivery as expressed through a concept of operation.

The decomposition methodology was used for operational and functional analysis, which enabled complex problems to be broken down into simpler and more manageable problems. Operational and functional analysis was conducted at a system-of-systems level that enabled better appreciation of complementary functions between the ground combat vehicles and mobile air defense systems. A model-based systems engineering tool (Vitech Core 9) was used to generate an interlinked framework that allows for iterative work while maintaining track of follow-on changes. Subsequently, measures were defined to ensure overall likelihood of mission success and functional performances. The overall measure of effectiveness was defined as neutralization of adversary surface-to-air missiles; the overall measure of merit was defined as the survivability of maneuver

formation. For each identified function and process, measures of performance and merits were identified respectively. These measures would form the main inputs to the next stage of the assessment framework.

Owing to the multiple factors that may affect the design of the mobile air defense system, design of experiment was used to expedite the assessment process. Other than measures of merit and performance generated from the system engineering process, input signal factors to the design of experiment also included factors related to combat survivability. While combat survivability (encompassing the 12 concepts for reducing susceptibility and vulnerability) is well established for aircraft platforms, combat survivability design consideration for land platforms currently utilizes a few select susceptibility or vulnerability reduction concepts. Inclusion of combat survivability within the factors that determine the design of the mobile air defense system ensures combat survivability is considered early in the design phase, thus preventing the need to conduct costly changes to incorporate combat survivability enhancements later on. The requisite components for a design of experiment comprise signal factors, noise factors, and responses. In order to determine noise factors, scenarios representative of typical military missions were generated to enable the distillation of noise factors that although uncontrollable, affect the performance of the mobile air defense system. The consideration of noise factors in the design of experiment allowed for a more representative performance assessment. In lieu of combat data, the assigning of responses was based on a "better- or worse-off" comparison between factors. The design of experiment was conducted using JMP 11 Pro statistical analysis software.

The results of the design of experiment are indicative of real world trends. Based on the design of experiment results, having short detection and engagement ranges is most critical for mobile air defense systems. In addition, long detection range could enhance performance. The exposure time of the maneuver unit formation to threats was also identified to be a high significance factor. This result is supported by real world trends in that most existing mobile air defense systems have a fire-and-forget system to minimize exposure time.

A systematic and interlinked assessment framework for the acquisition of a mobile air defense system has been developed. The use of model-based systems engineering tool and statistical analysis software is envisaged to expedite the assessment process significantly. Further validation of the framework with the use of combat data would enhance the accuracy and precision of the assessment results.

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ACKNOWLEDGMENTS

I thank the Defence Science and Technology Agency (Singapore) for this wonderful opportunity to study at the Naval Postgraduate School. In addition to acquiring knowledge from the curriculum, I have gained even more from the vastly experienced faculty.

I dedicate this thesis to my advisor, Professor Gary Langford, Ph.D. Thank you for your kind advice, patience, and guidance. You never fail to amaze me by applying seemingly inapplicable methods to solve problems. Suddenly everything seems possible. Thank you for making our weekly discussions so inspiring.

To Professor Douglas Nelson, Ph.D., thank you for providing your experience, insightful comments, and edits to make my thesis a better read. Special thanks are merited for Professor Christopher Adams. Your experience and knowledge in combat survivability was extremely valuable in making this thesis relevant.

I thank my mentor, Mr. Chua K.K., for making all this possible. Blunt as they are, your unconventional methods are interestingly effective. You taught me many life skills not found in textbooks.

To my family, thank you for being wonderfully supportive during the course of my study. To my dearest grandfather, thank you for caring for us in your unassuming ways. I wish you could have seen me graduate.

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I. INTRODUCTION

Ground combat vehicles are susceptible to aerial threats. The formation may be in unfamiliar territory and without established local air defense support during maneuver. Mobile air defense may be required to increase the survivability of ground combat vehicles during movement. Depending on the present threat and operation area, the required architecture of mobile air defense systems may vary.

The acquisition of a mobile air defense system or any weapon system is seldom a straightforward decision. Decision-makers may be pushing for what is wanted versus what is needed. What is wanted could be the latest trend, incorporated with new-edge technology, and a fierce-looking system. What is needed could actually be a simple, effective, and plain-looking system that utilizes mature technology. In addition, it is not uncommon for people to have a "bigger the better," "further the better," or "more expensive the better" mentality. However, the key point is to have a system that fulfills capability needs in response to the identified threats in the envisaged scenario. Similarly, the Department of Defense (DOD; 2010) defines capability as the ability to achieve a desired effect under specified (performance) standards and conditions through combinations of ways and means (activities and resources) to perform a set of activities.

The process of assessing what is needed may be daunting for the less experienced program managers. In addition, managers with different backgrounds may have a different appreciation of mobile air defense. Since the end of the Korean War, there has been less emphasis on the needs of mobile air defense. This situation is not helped by the air superiority of the United States in recent conflicts. Program managers with in-depth experience relating to mobile air defense may not be readily available. In view of the potential socio-political influences, the use of a systematic process helps to reduce human-related bias and provide a true representation of the capability need.

Consequently, the aim of this thesis is to provide a systematic and holistic framework that could be used to aid the program manager in the decision-making process concerning which type of mobile air defense system is needed. Since such assessments often require significant effort due to multiple variables involved, this framework also seeks to enhance the efficiency of the decision process by incorporating the use of models and statistical tools.

A. METHODOLOGY

Using a systems engineering approach, this study begins by looking into the capability needs for maneuver forces. These needs are matched to Joint Capability Areas (JCAs) defined by the DOD. Stakeholder analysis is conducted to establish the needs and concerns of stakeholders. Stakeholder analysis also helps to shape the measures used to evaluate the suitability of alternative designs later in the program. The next step is to define the operational concept, commonly communicated via DOD Architecture Framework (DODAF) operational view one (OV-1). Subsequently, operational analysis is conducted to determine the activities required to achieve the mission objective. Operational activities are commonly shown via DODAF OV-5b. The operational activities allow for the derivation of required functions to implement the operational activities. To ensure all operational activities are addressed, a mapping of operational activities to functions is conducted. Functional analysis results in a functional hierarchy allowing the conduct of component analysis. Functions are performed by components, thus a function to component mapping is conducted to ensure all functions are addressed. In defining the physical architecture, due to the many possible design parameters for a mobile air defense (MAD) system, a design of experiment (DOE) approach is used to identify significant factors of a MAD system for the defined operational concept. The results of the DOE aid the program manager in deciding on the most suitable MAD system design. The methodology for this thesis is summarized in Figure 1.

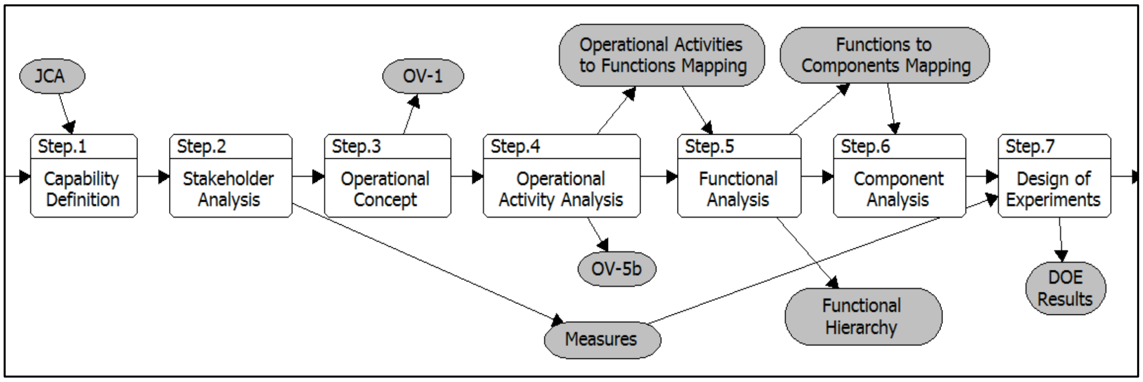

Figure 1. Thesis Methodology

B. THESIS ORGANIZATION

Chapter II provides the historical background of maneuver forces—their evolution and relevance in today's military operations. The recent trends with regard to threats faced by maneuver formations are also addressed. Subsequently, the concept of active and layered air defense is discussed. The recent acquisition history of mobile air defense systems in the United States and mobile air defense experience in recent conflicts are recounted in order to establish the capability need for mobile air defense. A brief categorization of current mobile air defense systems in the world is presented to provide the reader a sense of possible physical architectures for mobile air defense systems.

Chapter III describes the systems engineering process used with regard to the acquisition of a mobile air defense system. Capability needs are first established with reference to JCAs followed by stakeholder needs. From the identified capability needs and concept of operations, operational activities needed to achieve the capability needs are determined. Operational activities enable the identification of functions needed to implement the operational activities and subsequently the components to perform the requisite functions. The determination of measures of effectiveness, merit and performances is also discussed.

Chapter IV describes the use of DOE to facilitate the analysis of different factors that may affect the design of the MAD system. The rationale for the selection of experiment design, signal factors, noise factors, and experiment responses are discussed accordingly. Taguchi's orthogonal array, which allows lesser runs to be analyzed without sacrificing significant resolution in the results, was used. The signal factors and the associated levels are discussed. Scenarios were built in order to determine noise factors. In lieu of the lack of combat data, significance for each run was assigned as responses. The DOE was conducted using JMP Pro 11 statistical software.

Chapter V presents the results of the DOE. Significant factors based on the results of the design of experiments are highlighted. Chapter VI presents the insights from the DOE results, concluding remarks, and potential areas of future research.

II. LITERATURE REVIEW

This chapter provides background information upon which this thesis is built around. The following section will cover the history, evolution, and relevance of maneuver capability to modern warfare. Subsequently, threats to maneuver forces and background information on active and layered air defense in general will be discussed. The need for mobile air defense capability for the U.S. Armed Forces in relation to the history of mobile air defense in United States will also be addressed. A review of current mobile air defense systems in the world is included to provide a sense of possible physical architectures for mobile air defense.

A. MANEUVER CAPABILITY

This section describes the evolving role of maneuver forces. It also establishes the relevance of maneuver capability in modern times.

1. Symmetric and Asymmetric Warfare

In the most original and symmetrical type of warfare, opposing forces face each other with similar types of forces (Smith 2003). In asymmetric warfare, tactics different from what is normally expected are used. Bennett, Twomey, and Treverton (1999) refer to asymmetric warfare as strategies that are not considered standard or do not directly combat the strengths of the adversary. In ancient times, maneuver tactics were considered a form of surprise attack. When the adversary was expecting or currently fighting a frontal assault, forces attacking from other directions (e.g., flanks or rear) could cause surprise and confusion, which increased the chances of routing the adversary. Such tactics are recorded in Sun Tzu’s Art of War (Sun and Giles 1910). In the Battle of Little Bighorn in 1876, General Custer split his forces and attempted to attack a village in three different directions so as to utilize the element of surprise and maximize damage (Baker 2002). Consequently, maneuver tactics could be viewed as asymmetric warfare.

In modern times, maneuver tactics have since become something that could be expected. The *U.S. Army History and Role of Armor* (Department of the Army 1974) states the role and missions of armor in offensive situations. The missions include (1) deep penetration and wide envelopment, (2) exploitation, (3) defense, (4) destruction of enemy formations, (5) reconnaissance/security, (6) close support of infantry, and (7) economy of force. The element of maneuver is especially prominent in economy of force, where a commander maneuvers armored forces to another area, or via an alternative route, to strike a decisive blow to adversary forces (Department of the Army 1974).

From a holistic perspective, maneuver warfare could now be considered to be a mixture of symmetric and asymmetric warfare, leaning closer towards symmetric warfare (Bennett, Twomey, and Treverton 1998).

2. Relevance of Maneuver Capability

The capability to maneuver remains relevant in modern times. During the Yom Kippur War, the late Ariel Sharon demonstrated the use of maneuver warfare when the Israeli armored divisions crossed the Suez Canal and exploited the gap between two Egyptian armies to establish a bridgehead (Zabecki 2008). This maneuver resulted in arguably the most decisive turning point of the war. The protection and firepower of ground combat vehicles (GCVs) made them most suitable for such operations. The term GCV is used generically in this thesis in reference to ground vehicles used in maneuver warfare that may include main battle tanks and infantry fighting vehicles. During Operation Iraqi Freedom, the speed and firepower of the U.S. GCVs were exploited. The 1st Marine Expeditionary Unit covered a total of 808 kilometers in 17 days (Kennedy 2006), possibly the deepest and furthest penetration for a maneuver force in modern military history.

Maneuver forces are able to fulfill a variety of missions in both offensive and defensive scenarios. The DOD recognizes the utility of such a capability and has included maneuver capability as part of the JCAs. JCAs are described by the Deputy Secretary of Defense in the Joint Capability Area Management Plan (DOD 2010a) as the capability management framework of the DOD.

B. THREATS TO MANEUVER FORCES

The potential threats to maneuver forces are discussed in this section. Maneuver forces often have to operate at the forward areas of the battle. This situation results in maneuver forces being potentially exposed to threats from the air, land, and sea (for operations in proximity to the coast). The operational concept defined by this thesis is a land-to-land offensive maneuver, which is discussed in further detail in the Operational Analysis section in Chapter III. The following discussion is thus restricted to air and ground threats.

1. Air Threats

Air threats to maneuver forces are becoming more diverse. Besides the traditional threats of fixed wing aircraft and attack helicopters, unmanned aerial vehicles (UAVs) and unmanned combat aerial vehicles (UCAVs) are fast becoming a credible threat to maneuver forces.

a. Fixed Wing Aircraft

The armament of fixed wing aircraft capable of attacking ground targets could include 20 to 30 mm caliber gun(s), air-to-ground missiles, and bombs. For GCVs with substantial armor, aircraft guns(s) are unlikely to cause significant damage. However, for non-armored platforms, for example, the Avenger system mounted on a High Mobility Multipurpose Wheeled Vehicle (HMMWV), aircraft guns would be a threat. The use of missiles and bombs require fixed wing aircraft to fly low for better accuracy. The presence of anti-aircraft weapons would prevent fixed wing aircraft from flying at low altitudes, resulting in lowered accuracy of munitions, for example, dropped bombs. In addition, fixed wing aircraft move much faster relative to the maneuver force formation. Therefore, if the approach angle is unsuitable, the fixed wing aircraft may have to wait for the next pass before being able to conduct the attack. In recent times, the threat from fixed wing aircraft has been reduced compared to the attack helicopter.

b. Attack Helicopter

The armament of attack helicopters is similar to fixed wing aircraft with the exception of bombs. In addition, attack helicopters could also be armed with rockets. Attack helicopters have the ability to fly low under radar cover, often using local terrain to mask their signature and "popping-up" just before the attack. This modus operandi utilizes the element of surprise, resulting in the maneuver force having minimal reaction time. Consequently, threats from attack helicopters have been more predominant as compared to fixed wing aircraft.

c. Unmanned Aerial Vehicle

An increasing trend in recent times is the use of UAVs. UAVs are mainly used for reconnaissance to bring back the location of the maneuver formation so the adversary can launch offensive attacks. Some UAVs are now fitted with payloads, making them UCAVs and capable of conducting offensive attacks. UAVs/UCAVs are physically smaller in size compared to fixed wing aircraft or attack helicopters and are harder to detect. Due to the unmanned nature of UAVs/UCAVs, there is no possibility of human casualty. UAVs/UCAVs also cost significantly less than manned aircraft. A quick comparison of unit cost estimates places the MQ-9 Reaper at approximately $17 million (DOD 2012) versus $85 million (Butler 2013) for the F-35A (full production rate per unit in 2018). Due to the above-mentioned factors, the threat from UAVs/UCAVs is expected to increase over time.

d. Cruise Missiles

Cruise missiles as a threat to maneuver force formations are mentioned here for completeness. In the author's opinion, using a cruise missile to target a maneuver formation is not cost efficient. Cruise missiles are often fired from long ranges, which require significant time to cover the distance between the launch platform and the target. The BrahMos is currently the fastest cruise missile with a maximum range of 290 kilometers and speed of Mach 3 (Army-Technology 2015c). If fired at maximum range, the BrahMos reaches the target in about five minutes. Modern GCVs, such as the Abrams tanks and Bradley Fighting Vehicles (BFVs), can have maximum speeds of about 70 kilometers per hour (Army-Technology 2015b). In the time taken for the cruise missile to reach the intended location, the maneuver formation may have moved a significant distance away from the previous location.

2. Ground Threats

Ground threats to maneuver forces manifest in many forms. Depending on the operating environment, sources of potential ground threats include infantry weapons, medium and large caliber guns of ground vehicles and tanks, rockets, artillery, mortars, and guided munitions.

a. Small- to Medium-Caliber Gunfire

The threat from small to medium gunfire can originate from infantry or ground vehicles. Firearms carried by infantry range from 5.56 mm to 12.7 mm caliber rifles (Department of the Army 2011a). Ground vehicles often have self-protection armament (or secondary armament) ranging from 7.62 mm to 30 mm caliber guns (Department of the Army 2011a). Small to medium gunfire are not expected to pose a significant threat to ground platforms with armor protection. With regard to HMMWV and platforms with similar levels of protection, small to medium gunfire could cause damage to the platform and crew.

b. Rockets, Artillery, and Mortar

Rockets, artillery, and mortar (RAM) projectiles are fired from long ranges and generally without in-flight guidance. The probability of the maneuver formation sustaining a direct hit is likely to be low; however, collateral damage from fragments and blast effects could still cause damage to maneuver formation. To increase the survivability of maneuver formation, it is reasonable to reduce vulnerability by improving protection against fragment and blast effect. In regard to direct hits, it may be a better approach to improve survivability by reducing susceptibility. The maneuver formation may employ tactical movement to prevent adversary RAM crew from easily anticipating the location of the formation upon impact of the RAM projectiles.

c. Anti-Tank Guided Missile

Anti-tank guided missiles (ATGMs) can operate as a single system or as an integrated system with ground or air platforms. Some examples of ATGMs include the Spike, Milan, TOW, and Javelin. The effective range of ATGMs may vary from two kilometers (for Milan), to the eight kilometers (for Spike with extended range; Army-Technology 2014). ATGMs are commonly equipped with tandem charge warheads to defeat explosive reactive armor (Army-Technology 2014).

d. Rocket Propelled Grenade

Rocket propelled grenades (RPGs) are widely proliferated and easy to operate. RPGs are typically fired from the shoulder, similar to MANPADS. The most effective models (e.g., the RPG-7V) are fitted with tandem warheads to defeat the explosive reactive armor of tanks. The range of RPGs is typically within 300 to 600 meters (Department of the Army 2011a).

e. Tank Munitions

The author refers to tank munitions as the projectiles fired from the main guns of main battle tanks. For example, the main gun of the Abrams main battle tank would be a 120 mm caliber projectile. Tank munitions commonly range from 75 mm to 120 mm calibers (Department of the Army 2011a) with the exception of some Russian and Chinese systems with main guns of 125 mm caliber. As a general norm, the larger the caliber, the higher the destructive effect, for example, the kinetic energy or blast power (depending on the type of projectile). Tank munitions have significant penetrative ability and can cause serious damage to ground vehicles.

C. AIR DEFENSE

The DOD *Dictionary of Military and Associated Terms* (2014) defines *air defense* as direct (active and passive) defensive actions taken to destroy, nullify, or reduce the effectiveness of hostile air threats against friendly forces and assets. Active air defense is defined as direct defensive action taken to destroy, nullify, or reduce the effectiveness of hostile air and missile threats against friendly forces and assets including the use of aircraft, air defense weapons, weapons not used primarily in an air defense role, and electronic warfare (DOD 2014). Passive air defense encompasses all measures other than active air defense to destroy, nullify, or reduce the effectiveness of hostile air threats against friendly forces and assets (DOD 2014).

NATO categorizes active air defense systems broadly into very-short-range air defense (VSHORAD), short-range air defense (SHORAD), medium-range air defense, and air defense fighters based on the air space defended (Choenni and Leijnse 1999). Medium-range air defense is sometimes referred to as high-to-medium air defense (HIMAD). The range of a projectile is generally commensurate with the physical size of the projectile in order to have the required amount of energetic material for propulsion. Larger physical sizes translate to increased weight. With respect to MAD systems, the expected speeds of movement are in the ranges of 50 to 70 kilometers per hour. Consequently, HIMAD systems are less relevant within the scope of this thesis due to the physical size and weight of projectiles required. The following sections focus on VSHORAD and SHORAD systems.

NATO defines VSHORAD as systems that defend up to six kilometers in a horizontal direction and up to three kilometers in a vertical direction; SHORAD systems defend up to 12 kilometers in a horizontal direction and up to six kilometers in a vertical direction (Choenni and Leijnse 1999). The effective range of weapons and projectiles are often described using slant range. Slant range is defined as the direct line-of-sight distance between the air threat and defender. By a simple approximation using Pythagoras' Theorem, the author associates VSHORAD and SHORAD with slant ranges of six to seven kilometers and 13 to 14 kilometers respectively.

The type of air defense weapon defending the airspace is directly related to the effectiveness of threat suppression. Aircraft bombing could be carried out at different altitudes; bombing at lower altitude generally increases accuracy. The presence of air defense weapons force aircraft to carry out bombing at higher altitudes with reduced accuracy. Bombing with height of release over 15,000 feet (approximately four to five kilometers) is considered to be high-level bombing (DOD 2014).

D. CAPABILITY NEED FOR MOBILE AIR DEFENSE

Maneuver forces need to survive in order to execute the mission. Ball (2003) defines aircraft combat survivability as the capability of an aircraft to avoid or withstand a man-made hostile environment. Parallels could be drawn with regard to the survivability of ground combat vehicles. Combat survivability has an inverse relationship with vulnerability and susceptibility. When either vulnerability or susceptibility is reduced, survivability is increased. Vulnerability is defined as the inability of the platform to avoid a man-made hostile environment, while susceptibility is inability of the platform to withstand a man-made hostile environment (Ball 2003). Ball (2003) describes six ways to reduce susceptibility, namely, (1) threat warning, (2) noise jamming and deceiving, (3) signature reduction, (4) expendables, (5) threat suppression, and (6) weapon, tactics, flight performance, crew performance, and proficiency. The availability of mobile air defense support to maneuver forces suppresses the aerial threat, reduces susceptibility, and thus increases survivability of maneuver forces.

Tng (2014) studied the effects of sensing capability on the survivability of ground combat vehicles during ground force maneuver operations. The simulation results indicated that the presence of air defense capability was significant in improving the survivability of ground combat vehicles.

1. History of Mobile Air Defense in the United States

The capability need for mobile air defense for maneuver forces is not new. Antiaircraft gunners were the first U.S. troops in action during the Korean War, and World War II (Anderson, 2000). In a Congressional Budget Office study titled *Army Air Defense for Forward Areas: Strategies and Costs* by Lussier (1986), mobile air defense for maneuver forces was referred to as air defense for forward areas. The Army then had three SHORAD systems, namely Chaparral, Vulcan, and Stinger at the division levels. The Chaparral had low survivability in forward areas, and required long lead times for target acquisition; the Vulcan 20mm Gatling gun had limited effectiveness against aircraft threats (Lussier 1986). The Stinger was still operated as a MANPADS, and had limited mobility. The M247 Sergeant York Division Air Defense (DIVAD) anti-aircraft gun was intended to replace the ineffective Vulcan and Chaparral. The cancellation of the DIVAD program in 1985 (Kasser 2001) created a gap in the mobile air defense capability. In the interim, the MANPADS-under-armor (MUA) concept was adopted to provide mobile air defense to maneuver forces (Federation of American Scientists 2000). This involved Stinger MANPADS and gunners transported in armored vehicles during formation movement. The Stinger gunners had to dismount to engage the aerial threats when required. Such an operational concept was not ideal, as Stinger gunners would be exposed to enemy fire when dismounted.

The M6 Linebacker (a variant of the BFV) eventually filled the gap left by the cancellation of the DIVAD in 1997 (Army-Technology 2015a). The system was adapted from the Avenger system, which had Stinger missiles mounted on an HMMWV. The M6 Linebacker uses the same turreted system as the Avenger, but replaces the HMMWV with a BFV chassis that allows similar mobility to the tracked maneuver forces. The M6 Linebackers were converted back into BFVs in 2005 (Army-Technology 2015a).

2. Current State of Mobile Air Defense in the United States

The conversion of the M6 Linebackers back into BFVs left the United States with severely limited options with regard to mobile air defense. In the following section, the author discusses the possible alternatives if mobile air defense is required by the United States on short notice.

a. Current Fielded Systems

The nearest weapon system is the Avenger that has mounted Stinger missiles for air defense against aerial threats. However, the missiles are mounted on a wheeled platform. Wong and Huang (2006) analyzed the difference between wheeled and track vehicles using simulation models. The results showed that the amount of difference in traction between wheeled and tracked vehicles depended on the type of terrain. In general, wheeled vehicles had shorter contact length and area than tracked vehicles, leading to lower traction.

Consequently, the use of the Avenger for mobile air defense may result in air defense protection gaps due to the difference in mobility. For example, there may be difficult terrain where the tracked maneuver forces could overcome, while the Avenger would be left behind. In addition, on terrain more difficult than paved roads, the speed of the Avenger is likely to be less than the tracked maneuver forces.

One other option would be to revert to the MUA concept. However, in this age where high casualties are unacceptable, exposing Stinger gunners to enemy fire would be untenable.

b. Planned Replacement

At the time when the M6 Linebackers were converted back to BFVs, there were a few ongoing projects that could potentially be adapted for mobile air defense. They include the Medium Extended Air Defense System (MEADS), Surface Launched Advanced Medium Range Air-to-Air Missile (SLAMRAAM), and the Complementary Low Altitude Weapon System (CLAWS). The truck-mounted MEADS is more of an HIMAD system meant to replace the Homing All the Way Killer (HAWK) and Phased Array Tracking Radar to Intercept On Target (PATRIOT). The *U.S. Army Air and Missile Defense Operations field manual* (Department of the Army 2009) stated that SLAMRAAM was planned to replace existing Stinger systems. However, the SLAMRAAM is also truck-mounted and lacks the required mobility. The CLAWS was initiated by the Marines to replace Avenger systems (Strategy Page 2008). It is mounted on the HMMWV to fulfill the expeditionary requirements of the Marines. This seemed to be the closest fit for a mobile air defense solution. Overall, there seemed to be no intention of having a tracked short-range air defense (SHORAD) system to replace the M6 Linebacker. Nevertheless, the CLAWS, SLAMRAAM, and MEADS were cancelled in 2006 (Strategy Page 2008), 2011 (Dunnigan 2011), and 2013 (Hale 2012), respectively, leaving the mobile air defense gap unfilled.

c. Not a Requirement

Some may be of the opinion that the United States does not require mobile air defense. The last real air threat was probably during the Korean War in 1950 (Anderson

2000). Since then, the United States has been able to assert air superiority and maintain friendly skies during recent conflicts, for example, Kuwait (Lambeth 1993), Iraq, and Afghanistan (Krepinevich 2003). However, it should be noted that the adversaries faced by the United States in recent conflicts did not have significant air capabilities. However, if the United States were to engage an adversary of equal capability, air superiority may not be assured, even with technologically advanced air platforms. Anderson (2000) echoed similar views as he reiterated that mobile air defense remains relevant and that there will not be another Desert Storm where the United States reigned supreme in the skies. He may have been proven wrong for the moment, for the United States reigned supreme in the air yet again during the Iraq war in 2003; but who is to say the next war may not be against a technologically equal adversary? In a documented briefing to the Army on the future challenges of Army Air and Missile Defense by RAND, Lussier et al. (2002) highlighted that SHORADs are relatively cheap and easy to propagate on the battlefield. They remain a cost-effective option for maneuver force protection. More recently, in the U.S. Marine Corps *2014 Command Element Roadmap*, providing air and missile defense to maneuver forces was identified as a key enabler to the force during offensive combat operations (Department of the Navy 2014).

d. Reviving the M6 Linebacker

Some may view reviving the M6 Linebacker as a potential contingency plan; for example, the M6 Linebacker was integrated on the BFV chassis, and as long as the BFV remains in service, revival could be conducted on short notice if required. It should be noted that the M6 Linebacker was integrated on the BFV M2A2 Operation Desert Storm (ODS) chassis. There are already improved variants such as the M2A3 and M3A3 (Army-Technology 2015b). The integration compatibility of the turreted Stinger launcher and fire controls may not have been a requirement when the BFVs were upgraded. There may also have been upgrades to the Stinger missile. Consequently, there may be compatibility issues when attempting to integrate the turreted Stinger launcher, and fire controls onto the improved BFV variants. Such a plan also necessitates the requisition of BFVs at a time when they are most needed, thus reducing the number of BFVs available for operations and turnaround. Such a situation would not be ideal for war planners.

In addition, the spares for the turreted system may no longer be available. There is no literature to suggest that the removed turret components were salvaged and stored. Even if the removed turret components were salvaged and stored, they may not have been maintained. Last but not least, having the system does not equate to having the capability. The operators need to have been trained on the systems before being called upon to perform in real operations. Such is the U.S. maxim of "train the way you will fight" (Stytz, Banks, and Young 2003). The lack of training could lead to inefficiencies of the mobile air defense unit itself, between mobile air defense units, and maneuver forces.

Professor Christopher Adams lectures on Combat Survivability in the Naval Postgraduate School (NPS) in Monterey, CA. On January 13, 2015, at Watkins Hall, NPS, he described his deployment in Afghanistan during the first year of the war, "The aviators were ready and aircraft were stacked with munitions. The ground forces were just not used to calling for fire. Then they got really good at it." For different services to work together there has to be familiarity in order to have synergy in operations. If the maneuver forces, having not trained with mobile air defense, are required to work together on short notice, the effect will not be optimal.

3. Capability Gap

The earlier sections describe the current situation of mobile air defense in the United States. Current fielded systems, such as the Avenger, delivers only partial capability at most due to lack of terrain mobility and protection against ground threats. Reverting to MUA exposes Stinger gunners to enemy fire during engagement, which would be untenable. Potential air defense replacements including the MEADS, SLAMRAAM, and CLAWS were cancelled. There are no provisions for reviving the M6 Linebacker and if done on short notice, may lead to issues related to platform integration, and operational synergy.

The need for mobile air defense remains. There is a clear capability gap for the U.S. Armed Forces in the area of mobile air defense especially for maneuver forces operating in an environment with terrain.

E. EXISTING SYSTEMS

This section presents a selection of different types of MAD systems in the world. The systems are broadly categorized into MANPADS and integrated (wheeled and tracked) MAD systems.

1. MANPADS

MANPADS belong to the VSHORAD class of air defense weapons and require human gunners during operation. In the context of mobile air defense in this thesis, MANPADS and gunners are transported by vehicles, which provide the mobility required in the operational area. This mode of operation is similar to the MUA concept elaborated in the previous section regarding the history of U.S. mobile air defense. The two main types of MANPADS are fire-and-forget (FNF) and command-line-of-sight (CLOS). MANPADS could also be mounted and integrated onto wheeled or tracked platforms, as discussed in the later sections.

a. Fire and Forget

FNF MANPADS are mainly infrared heat seeking missiles. Upon the completion of trigger action by the gunner, the infrared seeker controls and guides the missile to the target. There are many MANPADs manufacturers in the world. Common FNF MANPADS include the SA-24, Stinger RMP Block II, and the Mistral 2. Most FNF MANPADS comprise a launch tube, missile, detachable firing mechanism, and coolant unit (to increase the sensitivity of the infrared seeker). The maximum range of the above mentioned MANPADS are about six to seven kilometers with missiles speeds between Mach 2.2 to Mach 2.7 (Department of the Army 2011b). The Stinger and Mistral are shown in Figures 2 and 3, respectively.

Figure 2. Stinger Missile (from Department of the Army 2011b, 6–56)

Figure 3. Mistral on a Tripod (from Department of the Army 2011b, 6–57)

b. Command Line of Sight

CLOS MANPADS are mostly laser-guided and commonly known as beam riders since the missiles ride on the laser beam for guidance. The gunner has to maintain track of the target upon the completion of trigger action until the missile reaches the target. Examples of CLOS MANPADS include the RBS-70 Bolide and Starstreak High Velocity Missile. The RBS-70 Bolide has a maximum range eight kilometers and missile speed of Mach 2 (Army-Technology 2015d). The Starstreak High Velocity Missile has a maximum range seven kilometers and missile speed of Mach 4 (Department of the Army 2011b). The Starstreak High Velocity Missile is shown in Figure 4.

Figure 4. Starstreak Lightweight Multiple Launcher with Missile (after Department of the Army 2011b, 6–55)

2. INTEGRATED MOBILE AIR DEFENSE SYSTEMS

This section introduces integrated MAD systems of the VSHORAD and SHORAD class. The author first differentiates integrated MAD systems by the type of mobility (e.g., wheel or tracked). Subsequently, each category is sub-categorized into oblique-launched and vertical-launched MAD systems. Oblique-launched MAD systems generally have shorter ranges; many of the systems are the result of integration of MANPADS with ground platforms.

a. Oblique-Launched Wheeled MAD Systems

Examples of oblique-launched wheeled MAD systems include the Avenger (integration with Stinger MANPADS), Albi (integration with Mistral 2 MANPADS), Crotale New Generation (NG), and SPYDER-Short Range (SR). Using information compiled from Boeing (2015), *World Equipment Guide Volume 2* (Department of the Army 2011b), and Rafael (2015), a brief summary of the four systems with respect to common characteristics of MAD systems is provided in Table 1. The Crotale hypervelocity VT-1 missile is able to achieve all round coverage without having a vertical-launched module. The high speed of the missile enables the achievement of 40-meter vertical rise before being directed to the target (Department of the Army 2011b). The Albi and Crotale NG are shown in Figures 5 and 6, respectively.

Table 1. Summary of Avenger, Albi, Crotale NG and SPYDER-SR Characteristics

	Avenger	Albi	Crotale NG	SPYDER-SR
Missile	Stinger RMP	Mistral 2	VT-1	Derby, Python 5
Range (km)	8	6	11	15
Fire on the Move	Yes	No	No	No
Guidance	FNF	FNF	CLOS	FNF, CLOS
Threat Information	External radar	External radar	Organic radar	External radar

Figure 5. Albi with Mistral 2 (from Department of the Army 2011b, 6–57)

Figure 6. Crotale NG XA-181 SAM Launcher Vehicle (from Department of the Army 2011b, 6–61)

b. Vertical-Launched Wheeled MAD Systems

The Vertical-Launched (VL) MICA is one example of wheeled vertical-launched MAD system. The following information regarding the VL MICA is provided in Army-

Technology (2015e). The VL MICA fires air-to-air MICA missiles fitted with either infrared or radar frequency seekers. In view of the two types of seekers, the system can be FNF or CLOS. The range of the MICA missile is approximately 10 kilometers, but does not have fire-on-the-move capability.

The MEADS belongs to the HIMAD class of air defense system, but is shown in Figure 7 to illustrate the typical physical structure of a wheeled vertical-launched air defense system.

Figure 7. MEADS Launcher (from Lockheed Martin 2013)

c. Oblique-Launched Tracked MAD Systems

Examples of tracked oblique-launched MAD systems include the M6 Linebacker (converted back to BFV M2A2 ODS since 2005), Stormer, and Pantsir S1. Using information compiled from *World Equipment Guide Volume 2* (Department of the Army 2011b) and Army-Technology (2015a), a brief summary of the three systems with respect to common characteristics of MAD systems is provided in Table 2. The Pantsir is shown in Figure 8.

Table 2. Summary of M6 Linebacker, Pantsir S1 and Stormer Characteristics

	M6 Linebacker	Pantsir S1	Stormer
Missile	Stinger RMP	9M335	Starstreak
Range (km)	8	12	7
Fire on the Move	Yes	Yes	No
Guidance	FNF	CLOS	CLOS
Threat Information	External radar	Organic radar	External radar

Figure 8. Pantsir S1 (from Department of the Army 2011b, 6–59)

d. Vertical-Launched Tracked MAD Systems

There are not many tracked vertical-launched MAD systems. One example is the Russian SA-15b also known as the Gauntlet or TOR-M1. The SA-15b has fire-on-the-move capability using 9M331 surface-to-air missiles with a range of approximately 12 kilometers (Department of the Army 2011b). An organic radar obtains threat information, which is used to guide the missile to the target via CLOS. The SA-15b automotive platform is able to travel up to 65 kilometers per hour on highways and 35 kilometers per hour on dirt roads (Department of the Army 2011b). The SA-15b is shown in Figure 9.

Figure 9. SA-15b/Gauntlet/TOR-M1 (from Department of the Army 2011b, 6–65)

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III. SYSTEMS ENGINEERING PROCESS

> Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on holistically and concurrently understanding stakeholder needs; exploring opportunities; documenting requirements; and synthesizing, verifying, validating, and evolving solutions while considering the complete problem, from system concept exploration through system disposal. (BKCASE Editorial Board 2014, 8)

In the previous chapter, the need for mobile air defense was addressed. GCVs remain susceptible to aerial threats especially during formation movement and deprived of established local air defense protection. Current fielded MAD systems are wheeled, thus delivering partial capability at best due to the lack of mobility. Reverting to using MANPADS to defend the maneuver formation exposes gunners to enemy fire during engagement and increases the potential of high casualties. Potential air defense replacements were cancelled due to budget constraints. Reviving the M6 Linebacker may encounter platform integration and operational synergy issues. Therefore, there remains a capability gap in the area of mobile air defense for maneuver forces.

In order to fill this capability gap, the DOD may acquire a MAD system. The systems engineering process is extremely useful for an acquisition project. The above quote from *The Guide to the Systems Engineering Body of Knowledge* (SEBoK) describes the systems engineering process as a systematic and holistic methodology. Stakeholder needs are defined leading to development of functional needs and subsequent fulfillment of functional needs by the physical architecture. Such an interlinked model allows for comprehensive tracking during design iterations to ensure stakeholder needs are addressed. Acquisition work is premised on having a set of requirements from which to carry out development or purchase of requisite materiel and resources. This approach ensures the final system or product is useful and achieves the intended objective(s). The systems engineering process for acquisition of a MAD system is described in this chapter. The method used in this systems engineering acquisition process is to first, define the problem; second, conduct stakeholder analysis; third, conduct operational analysis; fourth, conduct functional analysis; and fifth, generate the physical architecture. The result of this method that iterates between these five tasks is to characterize the system concept for delivery as expressed through a concept of operation.

A. MODEL-BASED SYSTEMS ENGINEERING

The multi-phased systems engineering process described earlier commonly results in many layers of interlinked information; for example, operational activities are implemented by functions, which are in turn performed by components. Manual tracking and updating of the relationships between the layers can be tedious. Model-based systems engineering is defined by INCOSE (2007) as the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later lifecycle phases. The author uses a model-based system engineering tool to aid the tracking and updating of interlinked information. The tool of choice is Vitech CORE 9, which supports DODAF Version 2.0 viewpoints integrated with requirements, analysis, and verification to provide a complete system definition (Vitech 2015).

B. PROBLEM DEFINITION

Ground combat vehicles are susceptible to aerial threats. During maneuver, the formation may be in unfamiliar territory, and without established local air defense support. Mobile air defense may be required to increase the survivability of ground combat vehicles during movement. The U.S. Armed Forces has a need to protect maneuver forces from aerial threats during movement.

1. Assumptions

In defining the problem statement, the overarching assumption was that the United States would be engaging an adversary of equal military might, and technological maturity. Such an assumption is reasonable considering the uncertainty of world affairs. One recent example is the strained relationship between the United States and Russia since April 2014 due to Russia’s alleged involvement in the internal state affairs of Ukraine.

The follow-on assumption would be that significant friendly fighter aircraft would be required in air-to-air combat with adversary fighter aircraft in an attempt to achieve air superiority. This assumption takes into consideration the increasing costs of building a fighter aircraft. Limited resources and the increasing aircraft cost would led to a reduction in aircraft fleet size in the U.S. Armed Forces. Aircraft may become more capable and multi-role, but they cannot be present at more than one location simultaneously. The preoccupation of friendly multi-role fighter aircraft in air combat results in a lack of available aircraft for close air support (CAS) to ground forces.

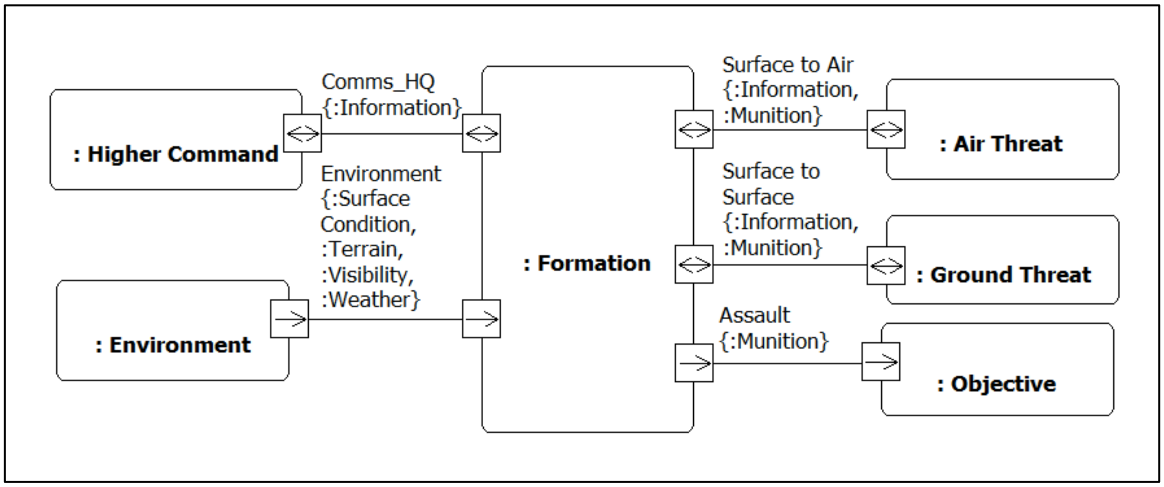
It is also assumed that the objective location for maneuver forces is heavily defended by adversary active surface-to-air missiles (SAM). To prevent heavy casualties in such a scenario, the use of friendly fighter for suppression of enemy air defense (SEAD) would not be considered.

2. Boundaries

Boundaries help to scope the design of the system by facilitating identification of what is considered within the system and what is external. System design is influenced by the interactions between the system and external environment. Energy, matter, material wealth, and information (EMMI), are the four main modes of interaction between entities (Langford 2012).

The MAD system itself is a system. It integrates with the GCVs in the form of a formation to realize a maneuver force acting as a system of systems (SOS). Langford (2012) defines an SOS as a set of systems that are both integrated and interoperable to achieve a set of meta-system functions in which all the component systems participate (to varying degrees). The maneuver force formation and MAD system share many common interactions with external entities. Consequently, the system context diagram was developed with the maneuver force formation as centroid.

The boundaries of the maneuver force formation are discussed via a system context diagram in Figure 10, which illustrates how the system interacts with external systems and environment during operation. The maneuver force formation is shown in its external environment.



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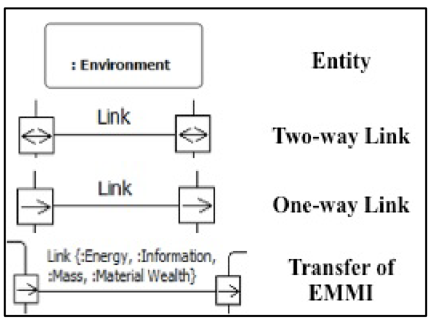

Figure 10. Context Diagram of Maneuver Force

In Figure 10, rounded rectangle boxes represent entities. The system under study, the environment, and physical objects (including interfacing systems), external systems, structures, and buildings (that interact with the system) are referred to as entities. Entities have to be linked in order to have interaction. It was mentioned earlier that objects interact with each other via the transfer of EMMI (Langford 2012). EMMI may be transferred via such links. Double-headed arrows represent two-way linkages, that is, EMMI could be transferred to and from the linked entities. Single-headed arrows represent one-way linkages, that is, EMMI could only be transferred from the originating entity to the linked entity. The type of EMMI transferred is shown in braces beside the link. A link could transfer more than one EMMI.

The maneuver force formation interacts with five main entities, namely, higher command, the environment, air threats, ground threats, and the mission assault objective.

a. Higher Command

The mission would have been tasked by higher command. During operations, higher command would want to be aware of the status of the mission. Consequently, the maneuver force formation has to provide status updates to higher command. Status updates could include situational reports, reconnaissance intelligence, weather conditions, and supply support levels. Based on the status updates, higher command may decide to issue new commands or to amend previous commands. Status updates and commands are considered information. Therefore, there is a two-way communication link transferring information between the maneuver force formation and higher command.

b. Environment

Upon commencement of the mission, the maneuver force formation is inserted into an operating environment. The environment imposes constraints on the maneuver force formation via one-way transfer of EMMI. Maneuver forces (in this context) are ground vehicles that need to interact with the traveling surface in order to move. Good traveling surfaces like paved roads improve the mobility of the maneuver force formation. Conversely, undulating terrain would greatly hinder movement of the formation. The terrain of the operating environment could have significant impact on the threat signature of the maneuver formation. Hilly terrain provides opportunities for cover and concealment during maneuver. Conversely, the formation would be more susceptible to detection when travelling in flat and open terrain. Visibility is of key importance especially for weapon systems that still rely on the eye of the operator to engage the adversary, such as MANPADS. Low visibility makes it harder to detect potential threats. The weather also affects the maneuver force formation. While precipitation is unlikely to affect the formation physically, the impact of adverse weather (e.g., snowstorms) would affect visibility and mobility.

c. Air Threats

The maneuver force formation interacts with air threats mainly via the transfer of information and munitions (mass). Information is transferred when the maneuver force formation detects, tracks, and identifies the air threats. Upon identifying the air threats, munitions would likely be used to engage the air threats. Although the MAD units are more suited to fulfill this role, the small arms capability of GCVs would also contribute towards killing or deterring the threat. Similarly, from the point of view of the air threats, information is transferred when the maneuver force formation is detected and identified. There is lesser emphasis on tracking of ground threats due to the lower mobility. Air threats could then use munitions to engage the maneuver force formation. In the case of UAVs, only information may be transferred, such as detecting and identifying the location of the maneuver force formation before passing the information to attacking units.

d. Ground Threats

Similar to air threats, the maneuver force formation interacts with ground threats mainly via the transfer of information and munitions. Information is transferred when the maneuver force formation detects and identifies the ground threats. Upon identifying the ground threats, munitions would likely be used to engage the ground threats. A similar interaction is expected for the ground threats with respect to the maneuver force formation.

e. Assault Objective

Once the maneuver forces have arrived at the objective location, assault of the objective using munitions would commence. The objective is unlikely to have significant protection at this stage, as all available defenses would have been deployed earlier to prevent the maneuver force formation from reaching the objective. Such a scenario is likely to involve the one-way transfer of mass, such as munitions from the maneuver force formation to the objective.

C. STAKEHOLDER ANALYSIS

Stakeholder analysis is conducted to identify the needs, objectives, and concerns of the major stakeholders in a program. Stakeholders are identified and ranked according to their interest and influence on the program throughout the program lifecycle. High influence stakeholders are often able to affect the direction of the program. Their needs and objectives could result in requirements for the program.

There are five main stakeholders identified in the acquisition of a MAD system, namely (1) higher management, (2) armed forces, (3) adversary, (4) defense industry, and (5) U.S. citizens. The needs, objectives and concerns of the respective stakeholders are discussed in the following section.

a. Higher Management

Higher management includes the U.S. Congress and DOD. They wield the highest influence with regard to the MAD system program. The three pillars of an acquisition program are performance, budget and schedule. Budget for the program has to be approved by Congress. Budget cuts could lead to reduction in capability or even cancellation. The mission of the DOD is to provide the military forces needed to deter war and to protect the security of the United States (DOD 2015). They possess the power to decide on the types of capabilities and systems required for the United States Armed Forces. Through the program executive office that manages defense acquisitions, the DOD also has close control over testing and evaluation of the MAD system. In regard to a maneuver mission, the objective of Higher Management is to prevail over the adversary while minimizing casualties. They would be interested in the MAD system as it affords protection to the GCVs, thus minimizing the risk of having casualties. Higher Management would be concerned if GCVs were unprotected in the presence of aerial threats.

b. Armed Forces

The Armed Forces include the U.S. Army, Marine Corps and Fighter Squadrons. The U.S. Army and Marine Corps operate GCVs including the M1 Abrams tank and BFV. The offensive maneuver mission as described in this thesis depends on GCVs for mission execution. Consequently, the United States Army and Marine Corp have high interest in the MAD system due to the much-needed aerial protection afforded by MAD systems during maneuver. Current interim measures include using the wheeled Avenger system that provides partial capability, or to bear the risk of aerial attacks. Consequently, the U.S. Army and Marine Corps would like to have a MAD system of high performance and quality. Fighter aircraft may not be able to advance to secure key areas due to the presence of adversary SAM sites. The offensive maneuver mission, if successful, neutralizes the adversary SAM capability. In order to neutralize the adversary SAMs, GCVs need to survive until arrival at the objective location. Aerial protection afforded by MAD systems increase the likelihood of survival of GCVs until arrival at the objective location. Fighter Squadrons thus have direct interest (primary) in GCVs and indirect interest (secondary) in MAD systems.

c. Adversary

It is often heard in defense circles that the adversary or threat always gets a vote (Butler 2015). The objective of the adversary is to protect key area(s) by killing incoming maneuver forces. The adversary has high interest in MAD systems as they reduce the effectiveness of their aerial capabilities when attacking incoming maneuver forces. At an SOS level, the presence of MAD systems as part of the formation indirectly increases the risk of adversary SAMs being neutralized, leading to key areas possibly being taken over. An effective MAD system may also result in the adversary having to improve the capability of their air and ground assets to neutralize the incoming maneuver forces.

d. Defense Industry

Defense industries are commercial entities. Their main aim is to generate revenue. By seeking to participate in the MAD system program, defense industries hope to gain experience, knowledge, and expand their portfolio. They also aim to increase market share and establish significant influence in the defense industry. As part of operation and maintenance, spares would be required for replacement and upgrade. Since most parts are likely to be special-to-type and proprietary, defense industries stand to generate steady downstream revenue. Defense industries would be concerned if they were not selected to build a part or the entire MAD system.

e. U.S. Citizens

The citizens of the United States are generally interested in state affairs. They are concerned about U.S. interests, but not too supportive of overseas military action. A poll conducted by Hart Research Associates/Public Opinion Strategies in October 2014 showed that 66% of responders felt that the war on Iraq was not worth it. Despite the interest, citizens have limited influence with regard to acquisition programs. On the other hand, citizens are also the taxpayers and final sponsor of the MAD system. High costs of weapon system acquisition could result in public disapprovals to continue programs as in the case of MEADS (Kennedy 2012). Subsequently, such actions could potentially influence the decision of the Higher Command to discontinue or reduce the budget of the program.

Based on the stakeholder analysis (discounting adversary), the overall stakeholder need is for the offensive maneuver mission to be successful so as to win the conflict or war. GCVs need to be survivable for the mission to be successful. In turn, GCVs require the aerial protection afforded by MAD systems. A highly survivable system also reduces casualty rates.

D. OPERATIONAL ANALYSIS

Maneuver forces are able fulfill a variety of missions in both offensive, and defensive scenarios. The Office of the Deputy Chief Management Officer (DCMO; 2015) defines JCA 3: Force Application as the ability to integrate the use of maneuver, and engagement in all environments to create the effects necessary to achieve mission objectives. Force Application is categorized into JCA 3.1: Maneuver, and JCA: 3.2, Engagement, as shown in Figure 11. JCA: 3.1 Maneuver is further categorized into Maneuver to Engage, Insert, Influence, and Secure (Office of DCMO 2015).

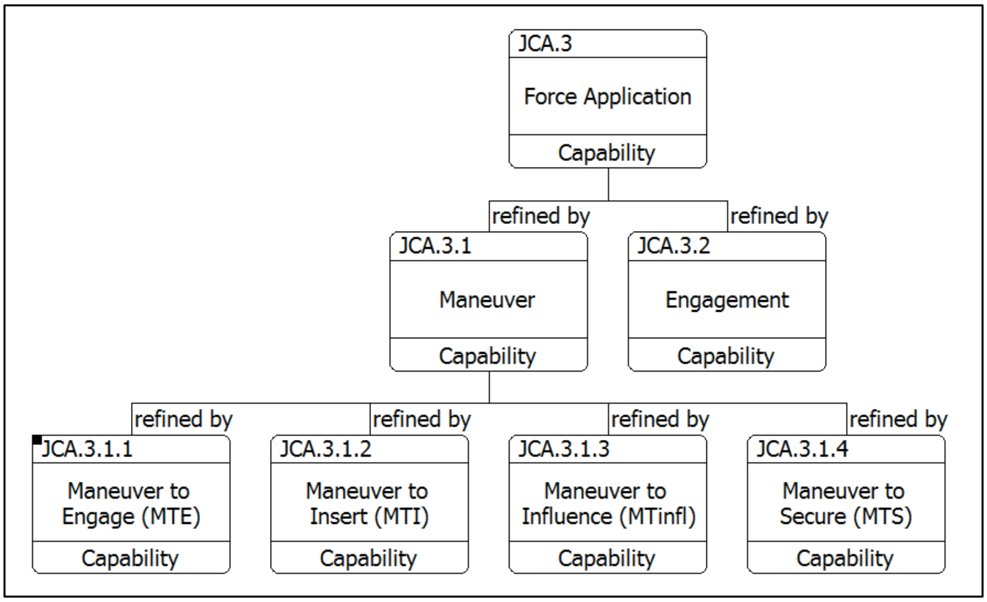

Figure 11. Joint Capability Area 3.0: Force Application

JCA 3.1: Maneuver is defined as the ability to move to a position of advantage in all environments in order to generate or enable the generation of effects in all domains and the information environment. In this thesis, the operational scope of maneuver forces is more focused towards an offensive capability over land to engage, insert, influence, or secure the objective.

1. Operational Viewpoint

The DODAF Version 2.02 uses the OV-1: High-Level Operational Concept Graphic to describe a mission, or scenario. The OV-1 illustrates the main operational concepts and interactions between the system, and the external environment (DOD 2010b).

Figure 12 shows the OV-1 for the maneuver force formation in a typical Blue Force versus Red Force scenario. Blue Force is trying to secure a key area (top left corner of Figure 12) controlled by Red Force. Air strikes are typically used in such scenarios; however, the key area is well defended by Red Force SAMs. Proceeding with air strikes may result in high casualties. A ground maneuver force is thus deployed by Blue Force to eliminate the Red Force SAMs. The Blue Force ground maneuver force is currently located at the forward area in relative proximity to Red Force controlled area. The forward area is shown in the bottom right corner of Figure 12, where a forward command post is located. The area air defense established at the forward area does not reach far enough to protect the ground maneuver force until arrival at the objective. Blue Force aircraft are unable to provide CAS due to the coverage of Red Force SAM. The Blue Force ground maneuver force thus has to close the distance between the forward area and the objective with organic MAD systems in the formation for protection against air threats. During movement, the ground maneuver forces may be attacked by Red Force air and ground threats.

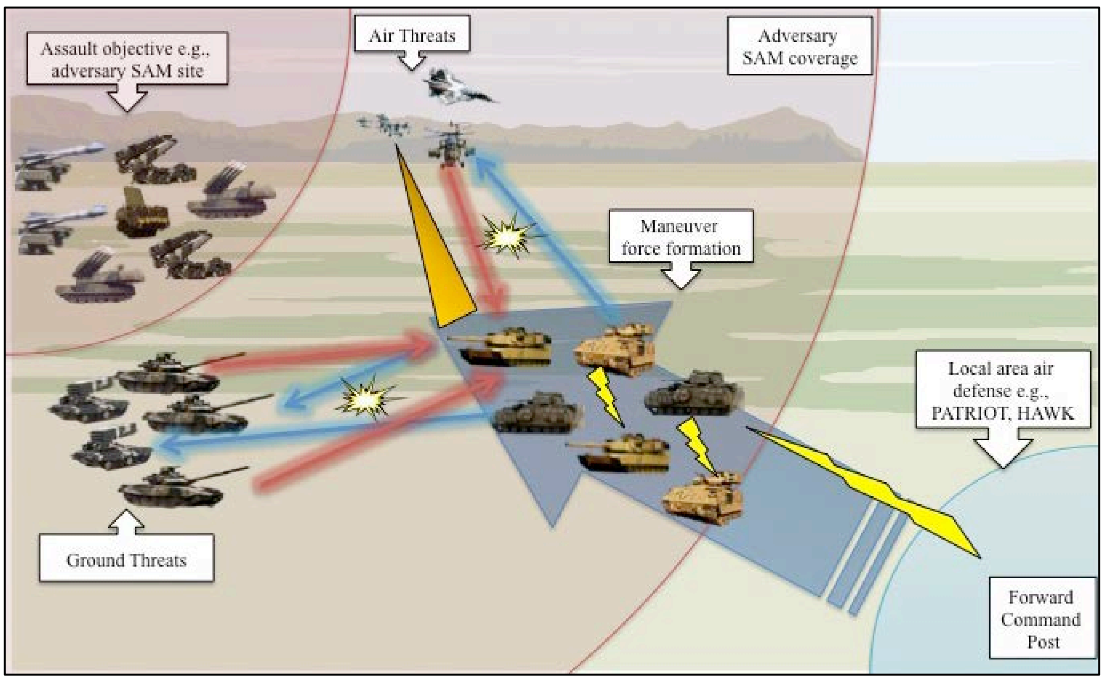

Figure 12. OV-1: Operational Concept of Offensive Maneuver Force

During the mission, the Blue Force MAD systems have to communicate with each other and the GCVs. As a formation, they provide status updates to higher command at the forward command post. In response, the higher command may issue new orders based on the status reports. If detected, the Blue Force formation may need to defend against the Red Force air and ground threats. The mission is over if Blue Force formation is killed by Red Force threats. However, if Blue Force formation survives the attacks by the Red Force air and ground threats, assault on the Red Force SAMs would commence.

2. Operational Activity Model

The DODAF Version 2.02 uses the OV-5b: Operational Activity Model to describe the operational activities (OA) that are normally conducted in the course of achieving a mission. The OV-5b illustrates the main operational concepts and interactions between the system, and external environment (DOD 2010b). Operational activities are enduring, that is, they are not specific to the physical system that performs the operational activities. The same operational activities are required to achieve the higher level maneuver force capability even if a new mobile air defense system is acquired. Figure 13 illustrates the operational activities required in order to achieve the maneuver force mission.

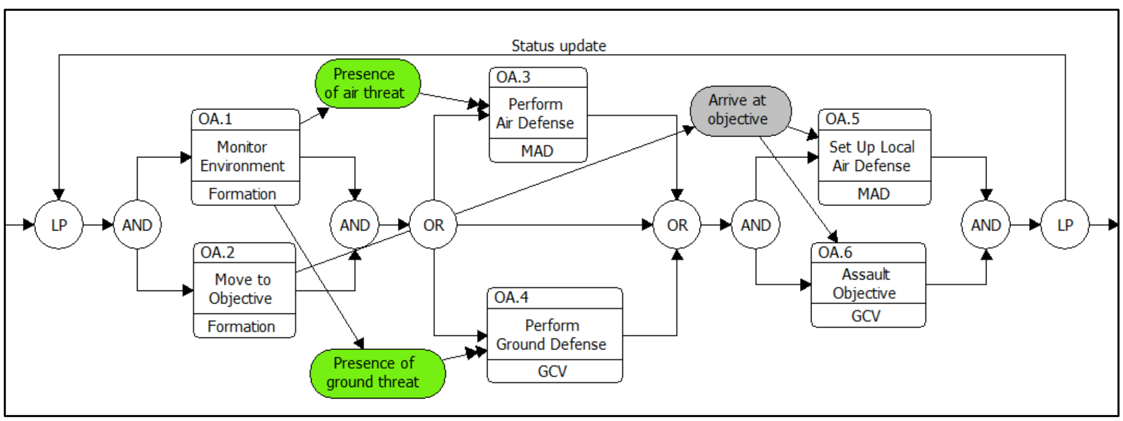

Figure 13. OV-5b: Operational Activity Model for Offensive Maneuver Force

All the operational activities are contained within a loop with starting and exit points shown as LP on the left and right of Figure 13, respectively. Throughout the entire mission, the formation provides status update to higher command, and receives new directions from higher command, if applicable. Upon starting the mission, the formation has to move towards the objective, and monitor the environment for threats or any abnormal conditions. OA.1 Monitor Environment, and OA.2 Move to Objective are the two operational activities executed respectively. Along the way, if air threats were detected, a trigger would be generated form OA.1 Monitor Environment. Triggers are shown in green in Figure 13. In the absence of triggers, the resulting OA would not be executed. If air threats were detected, OA.3 Perform Air Defense would be triggered. This operational activity is performed by the MAD systems. Similarly, if ground threats were detected, OA.4 Perform Ground Defense would be triggered. This operational activity is performed by the GCVs. If no threats were detected, the formation moves on smoothly. Outputs of OAs are shown in gray. As shown in Figure 13, outputs may serve as inputs for other OAs. OA.2 Move generates the output when the formation arrives at the objective, which serves as the input for OA.5 Setup Local Air Defense, and OA.6 Assault Objective. At this point, the GCVs execute OA.6 Assault Objective while the MAD systems execute OA.5 Set Up Local Air Defense to protect the GCVs in the interim until reinforcements arrive.

E. FUNCTIONAL ANALYSIS

Functional analysis is a technique that breaks down complex problems into smaller, simpler, and more manageable problems. A similar SOS concept is adopted for the conduct of functional analysis. The maneuver force that operates as an SOS comprises many functions and sub-functions. The main functions that are required by the SOS are F.1 Maintain Situational Awareness, F.2 Communicate, F.3 Move, F.4 Mitigate Air Threat, F.5 Mitigate Ground Threat, and F.6 Provide Power. In order to better understand what the maneuver force SOS and the MAD system are required to do; a functional analysis was conducted using the decomposition methodology. Decomposition by functions allows for an unbiased and non-solution specific analysis. Commencing the functional analysis at the SOS level allows a better appreciation of the overall mission that integrates the complementary functions that the MAD system and the GCVs may perform.

The OV-5b Operational Activity Model describes the operational behavior of the maneuver force formation. Operational behavior is implemented by system behavior, which in turn is the sum of functions of the system. By analyzing what system behavior is required to implement the operational behavior, the functions of the SOS can be determined. The SOS was first decomposed into main functions, which were subsequently further decomposed into sub-functions. The functional hierarchy for Mitigate Mission Threats is shown below in Figure 14 and comprises six main functions.

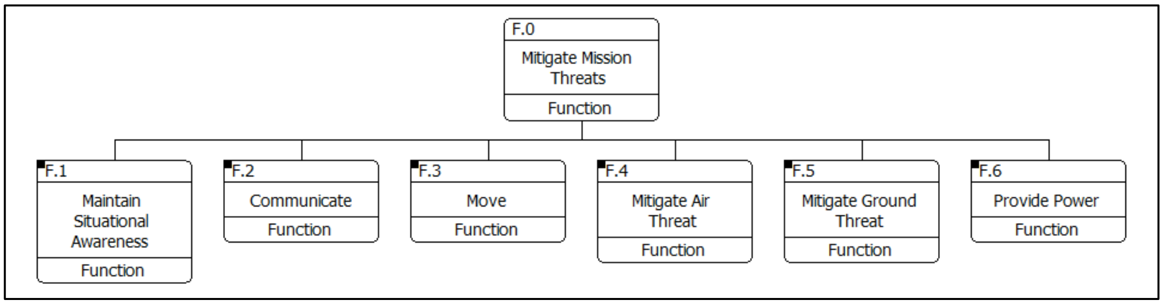

Figure 14. High-Level Functional Hierarchy for Mobile Air Defense Function

a. Maintain Situational Awareness

In order to mitigate mission threats, the SOS needs to know where the adversary is. Being aware of where the adversary is located relative to one's own position is commonly known as situational awareness. Maintaining situational awareness can be sub-divided into detect, track, and identify, as shown in Figure 15. The SOS needs to be able to first detect the presence of a potential threat. Subsequently, with repeated detections, the SOS would then be able to track the movement of the potential threat. The SOS also needs to be able to identify the threat in order for the operator to decide on engagement plans.

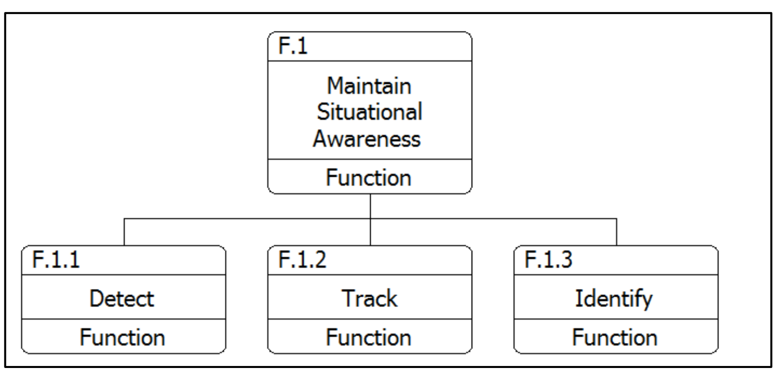

Figure 15. Functional Hierarchy for F.1 Maintain Situational Awareness

b. Communicate

The SOS needs to be able to communicate. Within the SOS, the mobile air defense units need to communicate with each other, and the GCVs of the maneuver force formation. As an SOS, it also needs to communicate with higher command. Communication could include many forms of information exchange including audio, visual, and data. Hence, the SOS must be able to receive, transmit, and process information. The functional hierarchy for the communicate function is shown in Figure 16.

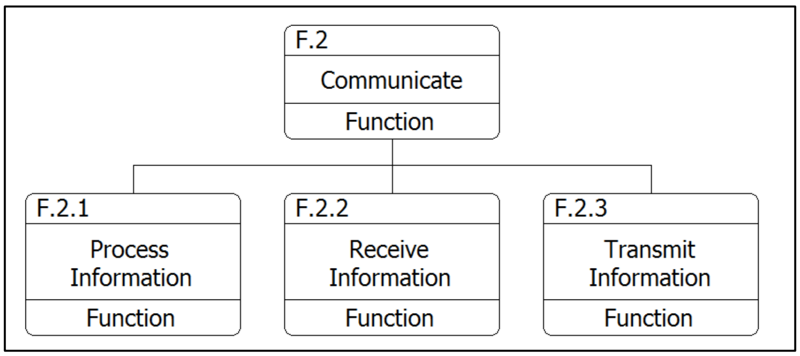

Figure 16. Functional Hierarchy for F.2 Communicate

c. Move

As a maneuver force, the SOS needs to be able to move. In order to move, each constituent unit within the SOS needs to be able to start, stop, and change direction. In addition, maneuver forces may need to operate in all kinds of terrain. Hence, the constituent units need to be able to climb (e.g., slopes), and possibly swim in water. The functional hierarchy for the Move function is shown in Figure 17.

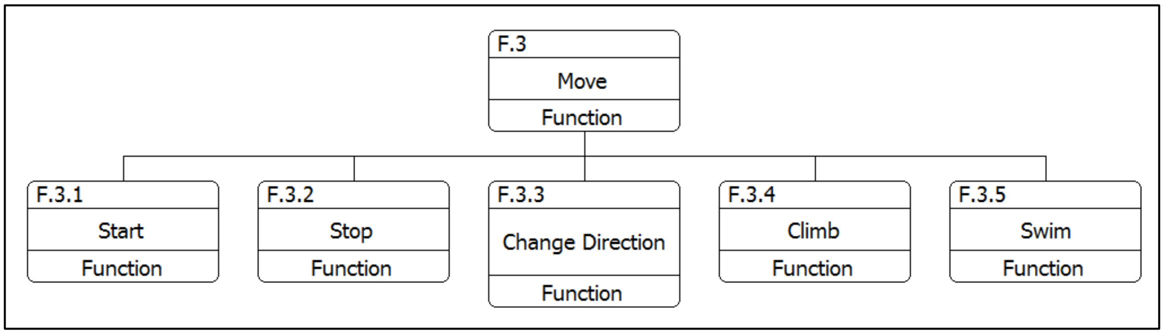

Figure 17. Functional Hierarchy for F.3 Move

d. *Mitigate Air Threat*

In order to defend the maneuver force formation against aerial threats, the MAD systems need to be able to engage the threat. The Mitigate Air Threat function could be further divided into launch, guide, and reload, as shown in Figure 18. The launch sub-function enables the system to send damage propagators to the threat. Damage propagators refer to the physical entity that causes damage to the platform (e.g., aircraft, tank, or ship). Since the threat is a moving target, the damage propagators need to be guided in order to home in on the target. This capability increases the chances of achieving a target kill. The launch mechanism that sends the damage propagator towards the intended target may have storage capacity for limited quantities of damage propagators. Reloading may be required when damage propagators are expended. Storage may also be required for storing spare damage propagators prior to reloading. An analogy could be drawn to an assault rifle where the gun assembly is the launching mechanism that sends the bullet (damage propagator) towards the intended target. The gunner reloads by changing magazines (storage).

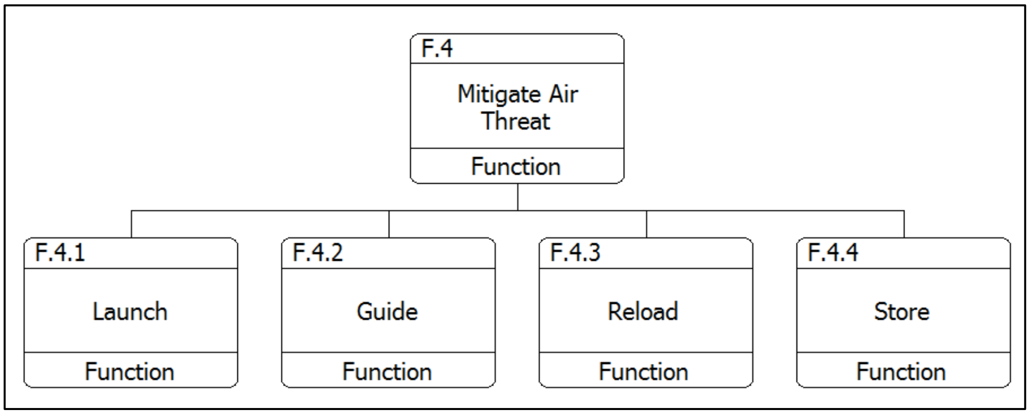

Figure 18. Functional Hierarchy for F.4 Mitigate Air Threat

e. *Mitigate Ground Threat*

The sub-functions (termed *function* in the figures) for mitigating ground threat are generally similar to that for mitigating air threat. Such functional decompositions represent the generic functions as descriptors, but each use of these generic terms may actually be quite different in terms of performance(s) and quality. For example, *launch* is generically defined as sending the damage propagator on its way to the target. However, in mitigating air threat, the launch trajectory of the damage propagator is from surface to air. For mitigate ground threat, the launch trajectory of the damage propagator is from surface to surface. The required launch speeds to engage air and ground threats may also differ. There lies the difference in performance and quality. Nevertheless, the use of generic descriptors suffices for the purposes of characterizing the system.

The Mitigate Ground Threat function is mainly performed by the GCVs. In order to engage the ground threat, the GCVs need to be able to launch damage propagators and guide them to the threat. The reload and storage functions are similarly required as in the case for F.4 Mitigate Air Threat. The four sub-functions for F.4 Mitigate Air Threat are thus reused for F.5 Mitigate Ground Threat.

In addition to the sub-functions in Figure 18, an added sub-function is required to mitigate ground threat. Increased survivability is dependent on reducing susceptibility and vulnerability. Due to the nature of surface-to-surface warfare, there is less focus on reducing susceptibility as compared to vulnerability. Being able to withstand damage from damage propagators of ground threats reduce the vulnerability of GCVs, thereby increasing survivability of the GCVs. The functional hierarchy for the Mitigate Ground Threat function is shown in Figure 19.

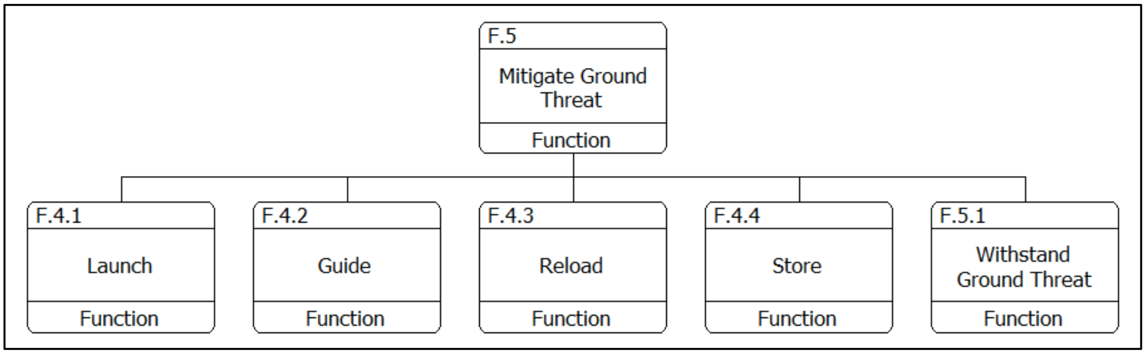

Figure 19. Functional Hierarchy for F.5 Mitigate Ground Threat

f. Provide Power

Modern weapon systems require significant power to operate. There no longer exists a purely mechanical weapon of war. Each system needs to be able to generate the required power for onboard systems to operate. In addition, if power generation could not be continuous, there may be a need to store the generated power for use at a later time when power generation is not ongoing or insufficient. Since there are many different subsystems onboard, there is also a need for power distribution sub-function to ensure the right power is provided to the different sub-systems. The functional hierarchy of Provide Power function is shown in Figure 20.

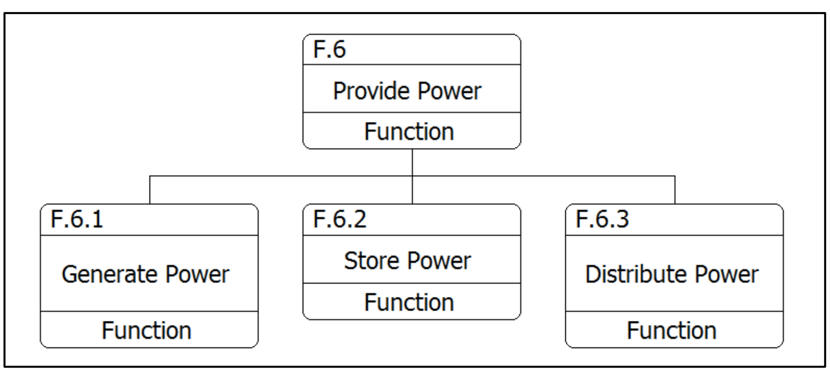

Figure 20. Functional Hierarchy for F.6 Provide Power

F. MAPPING OF OPERATIONAL ACTIVITY TO FUNCTION

Operational activities are implemented by functions. A mapping of operational activity to function is carried out to ensure all functions that are required to perform the operational activities have been identified. Figure 21 shows the mapping of OA.1 Monitor Environment to F.1 Maintain Situational Awareness, F.2 Communicate, F.3 Move, and F.6 Provide Power. The ability to detect potential threats is necessary to monitor the environment. The sub-functions of detect, track, and identity under F.1 Maintain Situational Awareness are thus essential. Once potential threats are detected, threat information has to be disseminated to the entire formation so as to level up the overall situational awareness. F.2 Communication enables the dissemination of information be it via audio, video, or data linkages. The monitoring of the environment has to be conducted while the formation is moving. If the formation has to stop in order to survey the environment, it results in a less than ideal situation where the formation is not protected during movement. The F.3 Move function working in conjunction with F.1 Maintain Situational Awareness enables monitoring of the environment while on the move. In order to maintain situational awareness, communicate and move, power is needed, and is provided by F.6 Provide Power function.

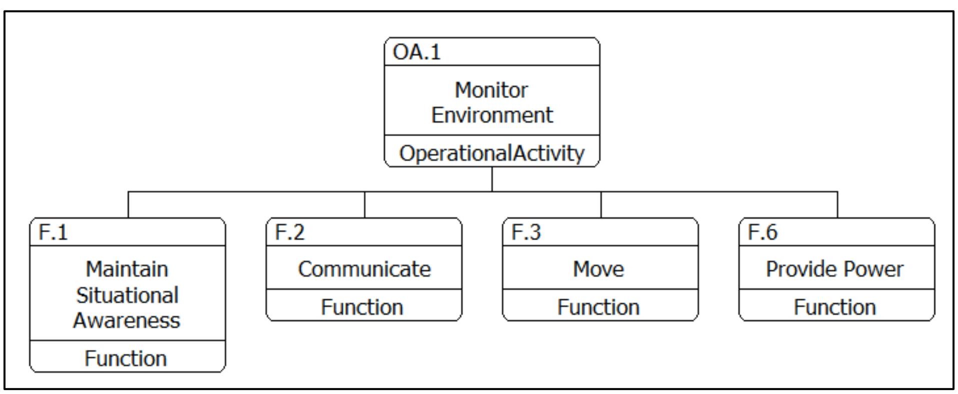

Figure 21. Mapping of OA.1 Monitor Environment to Functions

Functions F.2 Communicate, F.3 Move, and F.6 provide Power implements OA.2 Move to Objective, as shown in Figure 22. The formation may need to traverse different terrains while moving to the objective. F.3 Move comprises sub-functions that enable the formation to start, stop, change direction, climb over hills or swim across bodies of water. During movement, there is a need to communicate with each other. For example, if some units are moving too fast or slow, communication is necessary to get the units to adjust to the correct speeds. The F.6 Provide Power function provides the power necessary for the onboard systems to operate.

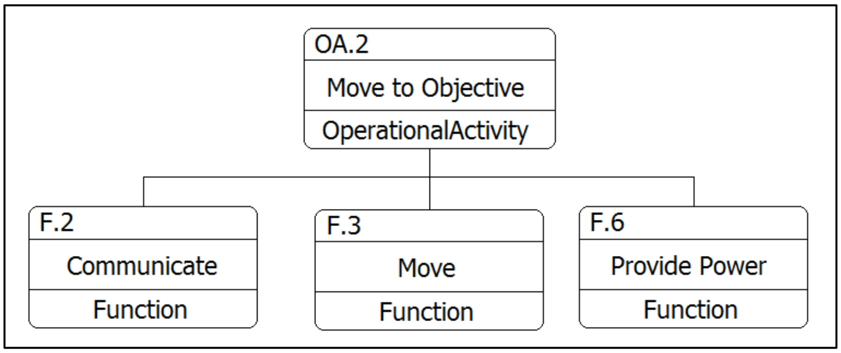

Figure 22. Mapping of OA.2 Move to Objective to Functions

Functions F.1 Maintain Situational Awareness, F.2 Communicate, F.3 Move, F.4 Mitigate Air Threat, and F.6 Provide Power implement OA.3 Perform Air Defense as shown in Figure 15. As illustrated in Figure 23, OA.3 Perform Air Defense is triggered when F.1 Maintain Situational Awareness detects a potential air threat. Consequently, F.1 Maintain Situational Awareness is needed to continue to track and identify the threat, in addition to detecting new threats. The location of the threat is constantly disseminated to the rest of the formation via F.2 Communicate, especially to MAD systems that are assigned to perform OA.3 Perform Air Defense. The formation needs to move via F.3 Move when air defense is performed. Movement could be tactical to scatter the GCVs around the MAD systems forming an all-round air defense and preventing the air threat from having a clear target. The MAD systems may also need to move into a better position to implement F.4 Mitigate Air Threat. In addition, if the formation is able to maintain movement while performing air defense, the survivability of the formation is increased. Performing air defense reduces susceptibility via threat suppression. Moving away from the air threat reduces susceptibility by lowering the probability of an engagement, as the air threat may need to reposition prior to launching a damage propagator. Ball (2003) defines the commencement of the engagement phase from the moment a damage propagator is launched towards the target (in this case the formation). In performing air defense, F.4 Mitigate Air Threat is arguably the main function. The launch, guide, reload, and store sub-functions enable the MAD systems to suppress the air threat. F.6 Provide Power is needed to operate systems including sensors, communication equipment, data links, weapon system, and platform.

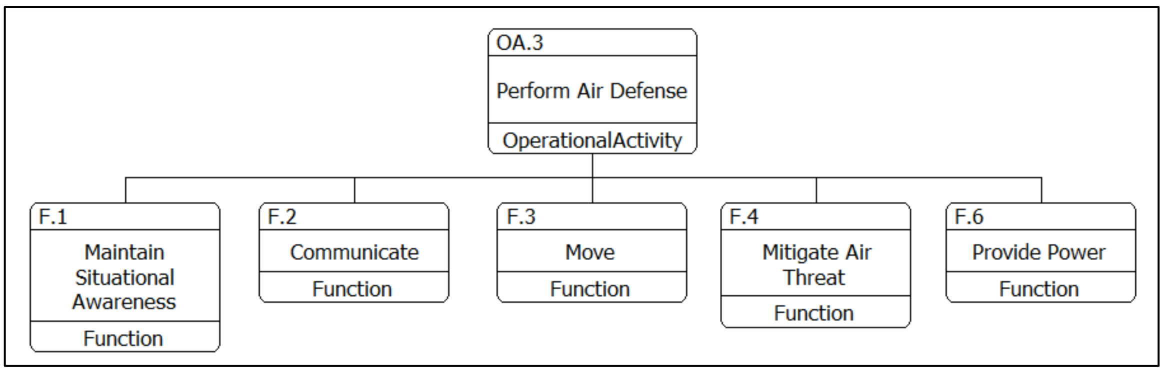

Figure 23. Mapping of OA.3 Perform Air Defense to Functions

Functions F.1 Maintain Situational Awareness, F.2 Communicate, F.3 Move, F.5 Mitigate Ground Threat, and F.6 Provide Power implement OA.4 Perform Ground Defense as shown in Figure 24. Similar to OA.3 Perform Air Defense, OA.4 Perform Ground Defense is triggered when F.1 Maintain Situational Awareness detects a potential ground threat. With respect to OA.4 Perform Ground Defense, F.3 Move is needed for tactical movement to engage the ground threat. F.3 Move also allows the formation to maneuver such that the MAD systems are protected from the ground threat by the GCVs. F.5 Mitigate Ground Threat comprises the sub-functions launch, guide, reload, store and withstand ground threat. The sub-functions enable the GCVs to engage the ground threats. Due to the nature of surface-to-surface engagement, an additional sub-function withstand ground threat is needed to increase survivability via reducing vulnerability.

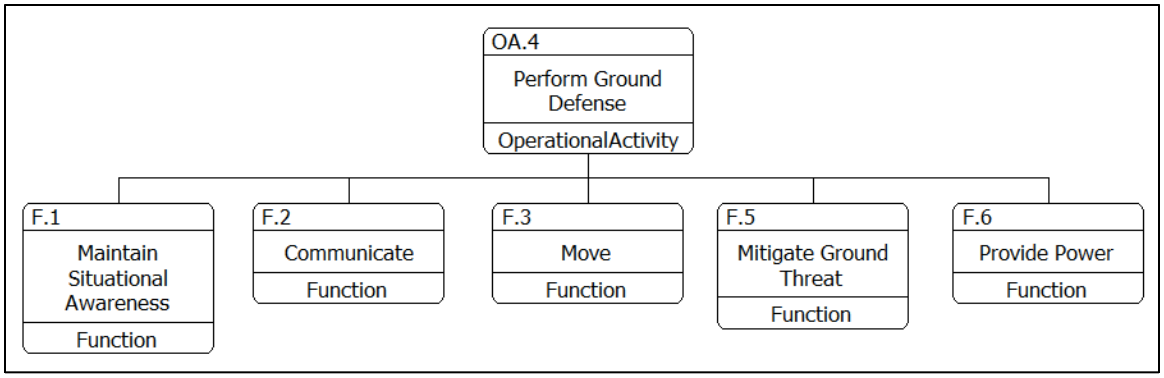

Figure 24. Mapping of OA.4 Perform Ground Defense to Functions

Functions F.1 Maintain Situational Awareness, F.2 Communicate, F.3 Move, F.4 Mitigate Air Threat, and F.6 Provide Power implement OA.5 Set Up Local Air Defense as shown in Figure 25. OA.5 Set Up Local Air Defense is similar to OA.3 Perform Air Defense. However, this is operational activity is executed when the formation has reached the objective location. The intent is to have all-round air defense while the GCVs assault the objective. In this operational activity, F.3 Move would be more applicable for the MAD systems to move to suitable locations in order to establish all-round air defense versus for tactical movement.

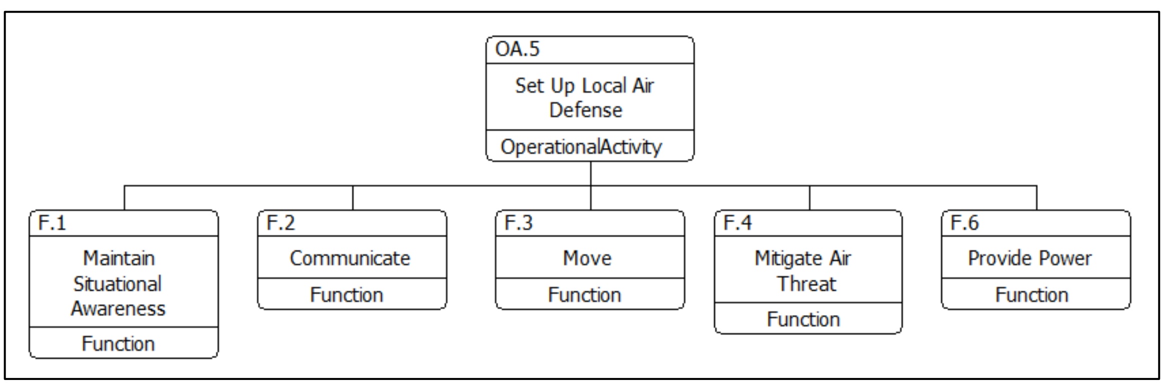

Figure 25. Mapping of OA.5 Set Up Local Air Defense to Functions

Functions F.2 Communicate, F.3 Move, F.4 Mitigate Air Threat, and F.6 Provide Power implement OA.6 Assault Objective as shown in Figure 26. While assaulting the objective, F.2 Communicate enables the GCVs to communicate with the formation to coordinate assault efforts and to avoid potential fratricide. The GCVs also need to move to assault the objective (e.g., to be in proximity to different SAM sites in the objective area). F.4 Mitigate Air Threat is referenced here in view of the relevant sub-functions of launch, guide, reload and store. As discussed earlier, functions for the purpose of modeling are generic descriptors with quite different performances and quality. F.6 Provide Power is needed to operate systems including communication equipment, data links, weapon system, and platform.

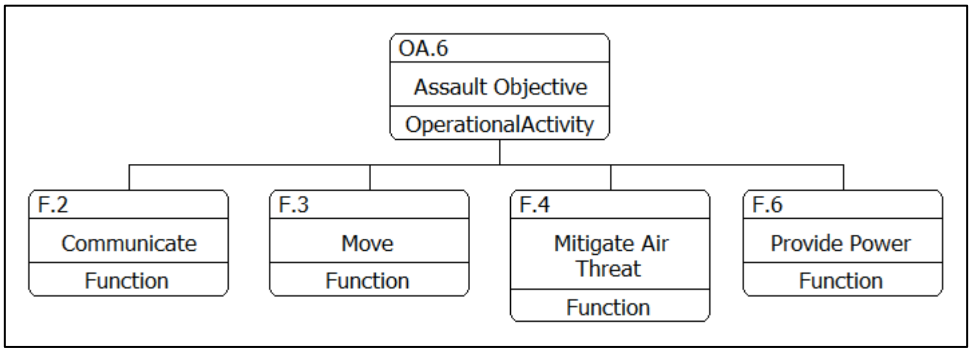

Figure 26. Mapping of OA.6 Assault Objective to Functions

Table 3 shows a summary of the mapping of all functions needed by the maneuver force formation to implement the operational activities to achieve an offensive maneuver.

Table 3. Mapping of Operational Activities to Functions

Operational Activity	Implemented by
OA.1 Monitor Environment	F.1 Maintain Situational Awareness F.2 Communicate F.3 Move F.6 Provide Power
OA.2 Move to Objective	F.2 Communicate F.3 Move F.6 Provide Power
OA.3 Perform Air Defense	F.1 Maintain Situational Awareness F.2 Communicate F.3 Move F.4 Mitigate Air Threat F.6 Provide Power
OA.4 Perform Ground Defense	F.1 Maintain Situational Awareness F.2 Communicate F.3 Move F.5 Mitigate Ground Threat F.6 Provide Power
OA.5 Setup Local Air Defense	F.1 Maintain Situational Awareness F.2 Communicate F.3 Move F.4 Mitigate Air Threat F.6 Provide Power
OA.6 Assault Objective	F.2 Communicate F.3 Move F.4 Mitigate Air Threat

The above functions are already evident in current mobile air defense systems, for example, the Avenger. The gap that leads to requirements is typified by functional performances and qualities. Take for example the F.3 Move function. The Avenger system is able to move. It has the ability to perform most sub-functions under F.3 Move, that is, start, stop, change direction, and climb. It does not have the ability to really swim, but it can traverse through large puddles of water. The performance of the *swim* function of the Avenger is thus of a lower level than that of the M6 Linebacker, which is fully amphibious. With regard to the *climb* sub-function, the Avenger would be able to climb a lesser slope than the M6 Linebacker on undulating terrain. Comparing the Avenger or the M6 Linebacker with gunners operating MANPADS, it is evident that the quality of function F.2 Communicate is of different levels. The Avenger and M6 Linebacker are designed to operate with target information input from Sentinel radars. Such a networked architecture allows for faster communication between detection and engagement of the air threat. In comparison, the gunner operating a MANPADS would have to manually scan the sky for air threats or rely on the verbal information from observers. So while the F.2 Communicate function exists when operating the Avenger, M6 Linebacker or MANPADS, the quality of communication could be markedly different. There lies the gap in performance and quality of functions (and sub-functions) that leads to requirements.

G. PHYSICAL ARCHITECTURE

Operational activities are implemented by functions, which are in turn performed by components. While there was benefit to conduct operational activity and function analysis at the SOS level, the physical architecture concerned is the system that is going to be acquired. Consequently, only the MAD system is addressed with respect to the components and physical architecture.

During design, there could be alternative components capable of performing the required functions. The main concern is regarding components that would likely have a major impact on the overall system design. Such components are identified for further analysis. Conversely, components that were unlikely to have a major impact on the overall system design (e.g., a battery for storing power) would be allocated to the subject matter experts (SMEs) who would be better suited to design or source for a component to suit system needs.

1. Allocated Components

Table 4 shows the allocated components for the MAD System. These components are unlikely to impact overall system design significantly and are allocated to SMEs for assessing the most suitable physical configuration.

Table 4. Allocated Components for MAD System

Functions	Performed by
F.1 Maintain Situational Awareness	
F.1.1 Detect	Sensor
F.1.2 Track	
F.1.3 Identify	Allocated to SME
F.2 Communicate	
F.2.1 Process Information	Allocated to SME
F.2.2 Receive Information	
F.2.3 Transmit Information	
F.3 Move	
F.3.1 Start	Platform
F.3.2 Stop	
F.3.3 Change Direction	
F.3.4 Climb	
F.3.5 Swim	
F.4 Mitigate Air Threat	
F.4.1 Launch	Weapon
F.4.2 Guide	
F.4.3 Reload	
F.4.4 Store	
F.5 Mitigate Ground Threat	
F.4.1 Launch	Allocated to GCVs
F.4.2 Guide	
F.4.3 Reload	
F.4.4 Store	
F.5.1 Withstand Ground Threat	Platform
F.6 Provide Power	
F.6.1 Generate Power	Allocated to SME
F.6.2 Store Power	
F.6.3 Distribute Power	

a. F.1.1 Identify

Identification functions in existing MAD systems are commonly fulfilled by an Identification of Friend or Foe (IFF) component. The proposed component to be used has to be compatible with current IFFs in inventory; for example, Russian IFFs would not work with NATO IFFs in view of differences in political associations and the need to safeguard national security. However, the selection of IFFs does not have a major impact on the overall system design. The IFF is often a relatively small component and does not affect the main functioning of the system.

b. F.2 Communicate

The aim of the Communicate function is to transmit, receive and process information. The type of communication component used—high, very high, or ultra- high frequency—is unlikely to affect the overall system design significantly. The SME has to ensure that receive and transmit stations are wired with compatible cables.

c. F.5 Mitigate Ground Threat

With regard to the MAD system, the engagement portion of the Mitigate Ground Threat function (i.e., launch, guide, reload, and store) are allocated to the GCVs.

d. F.6 Provide Power

Modern weapon systems need power to operate. However, power generation systems are also common and commercially available. If there is a platform, power is typically generated by the platform and stored in a battery or capacitor. Power distribution is commonly achieved via a power distribution bus. The SME has to conduct electrical load analysis to ensure all components are specified to suitable electrical loadings. While batteries could be physically significant depending on the storage capacity required, it is a space consideration and does not affect overall system design significantly. If necessary, space allocation could be further addressed during system design reviews and trade off analysis.

2. Non-Allocated Components

The MAD system is envisaged to comprise three main high-level assemblies. The non-allocated components would fall under one of these three high-level assemblies, namely, sensor, weapon, and platform. In the author's opinion and according to systems engineering best practices for design, component decomposition to two levels is sufficient (Buede 2009). There is little value in further decomposing the high-level assemblies to lower level components at this juncture as this thesis is focused on the identification of significant design factors for the MAD system. In a real-life acquisition program, upon identifying the significant design factors, the type of physical components and possible alternatives in implementing the required functions could then be explored. There are many techniques that aid the exploration of alternative components. One useful technique is the morphological analysis technique developed by Fritz Zwicky (1969) for examining multi-parameter relationships in complex problems. The main purpose of the systems engineering process up till this point is to demonstrate the systematic and interlinked process from stakeholder needs to identifying physical components. Table 5 shows the mapping of functions to high-level assemblies, thus ensuring that all functions are indeed addressed and performed by a component or sub-assembly within the high-level assembly. The next step would be to identify measures to evaluate the performance of the MAD system.

Table 5. Mapping of Functions to Components

Functions	Performed by
F.1 Maintain Situational Awareness	Sensor
F.2 Communicate	Platform
F.3 Move	Platform
F.4 Mitigate Air Threat	Weapon
F.5 Mitigate Ground Threat	Weapon
F.6 Provide Power	Platform

H. MEASURES

Measures are the independent variables that are reference points from which other items can be evaluated (Langford 2012). Measures of merit (MOMs) and performances (MOPs) are used in this thesis. Measures of effectiveness (MOEs) are discussed to distinguish from MOMs and in relation to MOPs for completeness.

MOEs are required by potential users to ascertain whether the product or service, decision or judgment, plan or outcome, technology or engineering is good for a purpose (Langford 2014). Therefore, an MOE represents the category of factors that influence the consequences of a function that results in mission outcome. On the other hand, an MOM represents the category of factors that influence the processes for achieving the likelihood of mission success. An MOE is differentiated from an MOM in that it is related to functions and consequence while an MOM is related to processes and likelihood. The Defense Acquisition University (2012) defines an MOP as system-particular performance parameter, for example, speed, payload, range, time-on-station, frequency, or other distinctly quantifiable performance features. MOPs are related to functions; several MOPs could be aggregated into an MOE. Each function results from interactions between the two or more physical objects from which at least one measure of performance is associated with that function (Langford 2012). The distinction of process (as related to MOMs) and functions (as related to MOPs) is fundamental to the mereology of objects and processes (Langford 2012).

Langford (2014) proposed an integrative framework for determining measures. Figure 27 shows the integrative framework, which considers interactions between the objective frame and subjective frame.

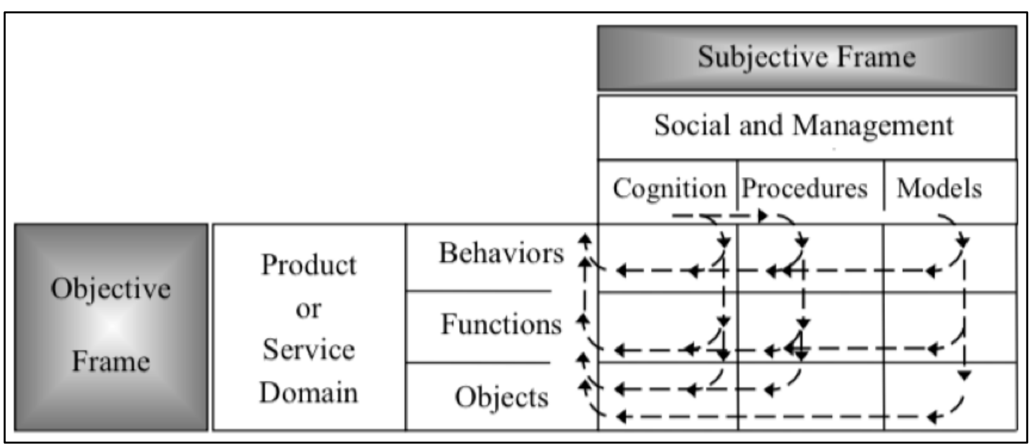

Figure 27. Integrative Framework (from Langford 2012, 88)

Langford (2014) provides the following description of the integrative framework. The arrows illustrate the sequencing of the interactions between the objects (objective frame) and the processes (subjective frame). This interplay begins with cognitive structures, progressing from subjective item to one objective item, then moving on to the next subjective item, from left to right. The perspective of management begins with the subjective frame with focus on the social and management issues (cognition, procedures, and models). From a technology perspective, the discussion often focuses on the objective frame. There are nine cardinal points within the framework, each resulting from the nexus of an item in one frame intersecting with an item in the other frame. These nine cross-frame intersections of the integrative framework are the nine domains of the measures.

The use of the integrative framework allows project objectives to be fulfilled. Figure 28 shows the potential measures determined from the interaction between processes and objects.

			Integration method		
			Processes		
			Abstractions (and reasoning)	Mechanisms, procedures, activities	Models, representations
OBJECTS	Product*Service	User behaviors (associated with or due to product*service)	Conceptualization pertinent to user behaviors due to product*service	Process and mechanisms describing user behaviors due to product*service	Models or representations of the user behaviors
		Functions (associated with or because of objects that comprise product*service)	Conceptualization delineating uses provided by product*service	Process and mechanisms achieving complete portroyal of product*service functions	Models or representations showing all functions
		Physical entities (associated with or because of objects that comprise product*service)	Identifying and interpreting the product*service physical artifacts, and ascribing meaning	Process and mechanisms resulting in the development of all physical elements	Models or representations of all physical elements

Figure 28. Integrative Framework—Nexus of Processes and Objects (from Langford 2012, 89)

In determining measures for the MAD system, the user behaviors associated with the MAD system are assumed to be perfect; for example, the stakeholders took the right decision in making the MAD system available to the maneuver force formation for protection from aerial threats. The top row of Figure 28 is thus excluded from further consideration.

The second row of Figure 28 is associated with the functions of the MAD system, which are also the main considerations for this thesis. In the second row, there are three categories for potential measures. As validated models to represent the functional performance of the MAD system are currently unavailable, this category is also excluded from further consideration. The remaining categories are the interaction of abstractions and reasoning; and interaction of mechanism, procedures, and activities with functions of the MAD system. From these two categories, the overall MOE is determined as the neutralization of adversary SAMs. The maneuver force helps the war cause by neutralizing the adversary SAMs, thus enabling the friendly air forces to conduct their missions to secure key areas. The maneuver force formation needs to survive (to a certain extent, notwithstanding expected attrition that does not affect the capability to complete the mission) in order to execute the mission. Survivability is a process and contributes to the likelihood of mission success. Survivability of the maneuver force formation (including the MAD system) is thus determined as an MOM. Both the MOE and MOM would be valid when viewing the maneuver force formation as an SOS. With regard to the MAD system, the MOM of survivability of the maneuver force formation is more relevant and thus adopted as the performance measure for the MAD system.

In functional decomposition, it is not uncommon for functions and processes to be considered together as in the case of the functional decomposition tool IDEF0 (Integrated Computer Aided Manufacturing Definition for Function Modeling) illustrated in Buede (2009). In this thesis, the author differentiates functions from processes but presents them in a combined table for ease of reference. Table 6 illustrates the MOMs and MOPs identified relating to the functions derived from functional decomposition conducted in previous sections. Although functions F.2 Communicate and F.6 Provide power are performed by components which have been allocated to the SMEs for design, the MOPs for these two functions are included in Table 6 for completeness. The list of identified MOMs and MOPs is not exhaustive and may be amended according to the threat, operations concept, and environment.

Table 6. Measures of Merit and Performance for MAD System

Functions		MOM/MOP	
F.1	Maintain Situational Awareness	MOP.1.1	Range of detection
		MOP.1.2	Platform speed during scan
		MOM.1.3	Number of intelligence sources
F.2	Communicate	MOP.2.1	Bandwidth
		MOP.2.2	Receive and transmit speed
		MOP.2.3	Processing speed
F.3	Move	MOP.3.1	Platform speed on road
		MOP.3.2	Platform cross-country speed
F.4	Mitigate Air Threat	MOP.4.1	Range of engagement
		MOP.4.2	Exposure time
		MOP.4.3	Coverage angle
		MOP.4.4	Platform speed during engagement
F.5	Mitigate Ground Threat	MOM.5.1	Ability to withstand up to 30 mm gunfire
		MOM.5.2	Ability to withstand one 120 mm round direct hit
F.6	Provide Power	MOP.6.1	Power storage capacity
		MOP.6.2	Peak and average power
		MOP.6.3	Percentage of equipment operating concurrently

1. Measures for F.1 Maintain Situational Awareness

a. MOP.1.1 Range of Detection

Four MOPs were identified for F.1 Maintain Situational Awareness. In maintaining situational awareness, a longer range of detection may allow more reaction time to determine the most suitable reaction plan, for example; the formation could form into a defensive configuration and wait for the air threat to be within range. Conversely, a shorter detection range may result in late detection and less time for reaction against the air threat.

b. MOP.1.2 Platform Speed during Scan

The MAD systems provide aerial protection to the GCVs in the maneuver formation. If the MAD systems have to stop or slow down when scanning for air threats, the GCVs will need to slow down as well in order to remain protected from aerial threats, and protect the MAD systems from ground threats. This mode of operation thus results in a longer overall exposure time of the maneuver formation to potential threats and extends the time of the mission. The faster the formation speed the more advantageous for survivability of the maneuver formation.

c. MOM.1.3 Number of Intelligence Sources

The greater the number of intelligence sources the MAD system could tap from, the better the chances of detecting a threat. Different types of sensors have different advantages; for example, long-range radars can scan a longer range but may lose resolution at shorter ranges. The ability to resolve the threat information from various sensors will be advantageous. Such a networked and resolved air picture may come at the expense of longer processing time in order to merge the threat information from multiple intelligence sources.

2. Measures for F.3 Move

The main consideration for platform would be speed. Maneuver missions are time critical. The longer the mission time, the longer the exposure time, and the lower the chances of success. The types of surfaces maneuver forces likely need to travel on are between paved roads and cross-country. The speed of the MAD system traveling on paved road and cross-country terrain would be a suitable measure of the performance of the Move function.

3. Measures for F.4 Mitigate Air Threat

Measures of performances were identified to measure the performance of F.4 Mitigate Air Threat function. Four MOPs were identified, namely, range of engagement, exposure time, coverage angle, and platform speed during engagement.

a. MOP.4.1 Range of Engagement

The range of engagement could be critical in certain operating environments. In open and flat areas, the advantage of a long range of engagement is immense. If the range of engagement of the MAD system is longer than that of the air threat, the MAD system could be engaging the air threat while having no chance of being killed. However, in closed terrain (e.g., forest and urban operating environments), the impact of a long range of engagement is largely discounted. Take for example an urban environment where the MAD system has already detected and identified an air threat that is within engagement range. However, there is a building blocking the line of attack. In this case the longer engagement range of the MAD system does not translate to any operational advantage.

b. MOP.4.2 Exposure Time

Exposure time is referred to as the time after shooting a round or firing a missile at the air threat before being able to take evasive actions. As discussed earlier, the speed of the platform when scanning for air threats affects the exposure time. The operating characteristics of weapon systems may also affect the exposure time. Take, for example, surface-to-air missiles that are commonly used to defend against air threats. If the missile is a CLOS system, upon completion of providing the launch signal (e.g., a complete squeeze of the trigger) the operator and the MAD system likely need to remain in the current position in order to provide a steady guidance for the missile. Conversely, if the missile is a FNF system, the MAD system is now free to take evasive maneuvers and actions upon completion of providing the launch signal. Infrared seekers that home in on infrared signatures (e.g., aircraft exhaust) passively are commonly used in FNF missiles. When operating such FNF missiles, there is no requirement for operator guidance during missile maneuver.

c. MOP.4.3 Coverage Angle

The term “cover my six” is military jargon for looking out for threats behind fellow friendly forces. Similarly, weapon systems are susceptible when attacked from an unexpected angle. In maneuver operations, the air threat could potentially be from any angle. The launch characteristics of weapon systems could affect the reaction time if the air threat is approaching from an angle that is not covered. There are two generic types of weapon system launch mechanisms, namely, oblique- and vertical-launched. Weapon systems that launch obliquely are generally slower to react. The weapon system needs to be slewed to the general direction of the air threat before launch. However, the time of travel for the damage propagator (i.e., missiles) is generally shorter as it travels in a direct path. Comparatively, vertical-launched systems are not constrained to any particular launch direction. They are normally launched vertically upwards before turning to the direction of the air threat. Vertical-launched systems react faster as they could be launched without slewing to the direction of the air threat. However, due to the trajectory shaping, the missile takes an indirect path that may lead to a longer time of travel.

d. MOP.4.4 Platform Speed during Engagement

Similar to MOP.1.2 Platform Speed during Scan, if the MAD systems have to stop or slow down when engaging air threats, the GCVs will need to slow down as well. Such operation modes would result in a longer overall exposure time of the maneuver formation to potential threats and also extends the time of the mission. The faster the formation speed the more advantageous for survivability of the maneuver formation.

4. Measures for F.5 Mitigate Ground Threat

The mitigation of ground threat is a process; MOMs are related to processes. Two MOMs are identified to measure the Mitigate Ground Threat process.

a. MOM.5.1 Ability to Withstand up to 30 mm Gunfire

With the exception of main battle tanks, 30 mm is generally the largest caliber for ground vehicle weapon systems (Department of the Army 2011a). The MAD system should be able to withstand gunfire from such common ground threats. Such a defensive capability would enable the GCVs to focus on neutralizing more significant ground threats, leading to higher overall formation survivability.

b. MOM.5.2 Ability to Withstand One 120 mm Projectile Direct Hit

It is reasonable to assume that adversary main battle tanks would target the MAD systems. Once the MAD systems are killed, the GCVs would be susceptible to aerial threats. Hence, the MAD systems should be able to withstand at least one direct hit from the main gun of the adversary main battle tank, currently assumed to be a 120 mm caliber equivalent. The three pillars of ground vehicle design are generally known to be armor, firepower, and speed. It is not practical to expect the MAD systems to have sufficient armor to withstand repeated hits from adversary main battle tanks. More armor would lead to reduced traveling speeds and possibly less weight allocation to the air defense weapon system.

5. Summary

Through the use of the systems engineering process, the study has proceeded in a systematic, interlinked, and iterative manner originating from capability needs to the definition of operational concept, followed by the determination of operational activities required to achieve the mission objective, and the derivation of required functions to implement the operational activities. The systems engineering process has now reached a juncture where there are many possible alternatives that could fulfill the physical architecture in performing the required functions. In addition, these alternatives may change depending on the operating scenario. In the next chapter, the use of design of experiment to aid the selection of physical architecture best suited for different scenarios will be discussed.

IV. DESIGN OF EXPERIMENT

In Chapter III, the systems engineering process enabled the systematic decomposition of capabilities into operational activities, functions and components. Measures of merit and performances were established. Each measure could be set at different performance levels. Assessing each permutation and combination of the measures would be onerous and likely to be inefficient. A DOE is utilized to identify the significant measures expeditiously. In a DOE, the main components are the layout of the experiment, signal factors and associated levels, noise factors, and the corresponding response of each experimental run. The following sections discuss the factors included for the DOE, type of DOE used, and the assigning of significance to response of each run in lieu of availability of combat data.

A. SIGNAL FACTORS

Signal factors are factors that can be controlled by the designer or engineer. The factors under consideration and the associated levels are first determined. In this thesis, the factors are restricted to two or three levels. The factors to be considered comprise mainly the MOMs and MOPs for the MAD system that are expected to exert significant influence on the overall design of the system. Other factors could also be included if assessed to be significant in system design. The systems engineering process provides a systematic and holistic approach to generate the require components. It does not constrain system engineers or program managers to adhere strictly to the functions and components generated by the process. Any additional areas of concerns could be included for analysis. For maneuver forces, one of the main concerns highlighted would be survivability. The maneuver force formation needs to be survivable in order to accomplish the assault mission. Being susceptible to aerial threats, GCVs depend on MAD systems to protect them, making them more survivable. Consequently, the MAD systems also need to be survivable in order to protect the GCVs, thereby allowing the GCVs to accomplish the mission. One of the techniques to increase survivability is via reduction of vulnerability (Ball 2003). Having critical component redundancy with effective separation (when one critical component is hit, the redundant critical component would not be affected by collateral damage) can in turn reduce vulnerability. The overall survivability of the maneuver formation was identified as an MOM. Having redundancy for critical components in the MAD systems would contribute to the overall survivability of the maneuver formation. Consequently, having redundancy of critical components has been included as two-level factors for sensor and weapon. Table 7 shows the selected factors with the associated levels. MOMs represent the contribution of processes to the factors in the DOE, whereas, MOPs represent the functional performances due to the functional requirements (Langford 2012).

Table 7. Factors for Design of Experiment

Factors		Level		
MOP.1.1	Range of detection	Short	Medium	Long
MOP.1.2	Platform speed during scan	Slow	Fast	-
MOM.1.3	Number of intelligence sources	One	Two	≥ Three
MOM.1.4	Sensor redundancy	Yes	No	-
MOP.3.1	Platform speed on road	Slow	Fast	-
MOP.3.2	Platform cross-country speed	Slow	Fast	-
MOP.4.1	Range of engagement	Short	Medium	Long
MOP.4.2	Exposure time	Short	Long	-
MOP.4.3	Coverage angle	< 180°	≥ 180°	-
MOP.4.4	Platform speed during engagement	Slow	Fast	-
MOM.4.5	Weapon redundancy	Yes	No	-
MOM.5.1	Ability to withstand up to 30 mm gunfire	Yes	No	-
MOM.5.2	Ability to withstand one 120 mm round direct hit	Yes	No	-

1. Three-Level Factors

From Table 5, there are three three-levels factors namely, detection range, number of intelligence sources, and engagement range. For detection and engagement ranges, there is a broad spread with the lower limit at about three to four kilometers and the upper limit possibly up to 15 kilometers onwards. Associating ranges with two levels (i.e., short or long) would not provide the kind of resolution that would be useful in influencing the system design. If the entire range is simply divided by half, the "short" level could range from three to eight kilometers. This association does not provide any distinction between

VSHORAD and SHORAD ranges. A three-level association thus allows a better resolution. As mentioned previously, the indicative states of short, medium, and long are used due to the lack of data. During an actual acquisition program where data is available, the indicative states could be replaced with discrete range values.

Using a similar thought process in associating levels for ranges, the number of intelligence sources is proposed to be associated with three levels, namely, one, two, and three or more. Having one intelligence source is quite the norm and most sensors would fall into this category. Assuming different kinds of sensors and with proper system integration, two intelligence sources should have a significant impact on providing better situational awareness. The benefits of increasing the number of intelligence sources follow the law of diminishing returns; that is, with each additional intelligence source, the benefit increases by a lower amount. Hence, the author deems it sufficient to have resolution between one, two, and three or more intelligence sources.

2. Two-Level Factors

Two-level factors are essentially “yes” or “no” states. Most of the factors fall under this category. In determining the platform speeds when traveling on road, cross-country, during scan, and during engagement, the main consideration is with respect to the GCVs. As the mission of the MAD system is to protect the GCVs, MAD systems are unlikely to be traveling significantly faster than GCVs. The main consideration is often whether the MAD systems are traveling at slower or comparable speeds to the GCVs, thus resulting in the two-level association for factors related to platform speeds.

The exposure time factor is associated with two-levels, short and long. The main consideration is usually whether the platform could engage in evasive maneuvers immediately upon engagement as in the case of an infrared passive homing FNF system. Hence, only two levels are associated with the exposure time factor.

Most directional weapon systems (oblique-launched) are capable of covering at least 180 degrees. The other class of weapon systems would be the vertical-launched systems that are capable of all round coverage with the possible exception of certain small angle(s) due to system limitations and/or physical blockages. Hence, an angle-by-angle analysis may be overindulgent. A two-level association for the coverage angle factor is assessed to be sufficient.

With regard to withstanding ground threat(s), the main consideration is whether the MAD system could withstand threats from generic ground threats and main battle tanks. Generic ground threats normally have armament up to 30 mm caliber guns; main battle tanks could have main guns of up to 120 mm caliber. A two-level association for each factor is sufficient to indicate the survivability of the MAD system against generic ground threats and main battle tanks.

B. EXPERIMENT DESIGN

This section discusses the considerations in the selection of experiment design. Common experiment designs include full factorial, where every possible combination is addressed, and optimized designs that allow fewer experiments to be conducted.

1. Full Factorial

When designing a simple experiment, the most straightforward method would be to consider all permutations and combinations. In statistics, this is known as the full factorial design. Each permutation or combination is known as a run. However, as the number of factors increases, the number of runs required increases very rapidly. Table 8 shows the number of runs required for a two-level full factorial (i.e., each factor can only have two different levels or values). With a three times increase (from two to six) in number of factors, the required number of runs increase by 16 times (from four to 64).

Table 8. Number of Runs Required for a 2^k Full Factorial (from National Institute of Standards and Technology [NIST]/Semiconductor Manufacturing Technology [SEMATECH] 2012)

Number of Factors	Number of Runs
2	4
3	8
4	16
5	32
6	64

If each factor had three levels, then the number of runs required becomes overwhelmingly large very soon. Table 9 illustrates the number of runs required for a three-level full factorial (i.e., each factor can have three different levels or values). With a similar three times increase (from two to six) in number of factors, the required number of runs increases by 81 times (from nine to 729).

Table 9. Number of Runs Required for a 3^k Full Factorial (after NIST/SEMATECH 2012)

Number of Factors	Number of Runs
2	9
3	27
4	81
5	243
6	729

For the MAD system, there were 10 proposed factors at two levels, and three proposed factors at three levels. This configuration presented two issues in regard to the use of full factorial designs for the experiment. Firstly, there are two-level and three-level factors. This non-homogeneity meant that a single full factorial, such as, two-level or three-level, would not suffice. Assigning an additional level to two-level factors to standardize all factors into a three-level 13 factor full factorial would require 1,594,323 runs. Arbitrarily fixing all factors to two-levels was possible, but would have resulted in loss of resolution with regard to some factors that may affect the design of the MAD system. Assuming the loss of resolution was acceptable, minimizing the number of runs by setting only two-level factors would result in 13 two-level factors, and still requiring 8,192 runs. Even with computers executing the experiment, significant computing resources, and time would be required. A more efficient method of assessing the significance of each factor at each level was thus needed.

2. Taguchi's Orthogonal Array

DOE is a statistical technique used to study the effects of multiple variables simultaneously (Roy 2001). The following introduction on DOE and orthogonal arrays are provided in (Taguchi, Chowdhury, and Wu 2005). R.A. Fisher when researching on methods of improving barley in agriculture first introduced DOE. Many including Japanese engineer Genichi Taguchi, researched DOE methods. Working upon the orthogonal array technique first introduced by Fisher, Taguchi proposed the use of level-labeled orthogonal arrays, which are now referred to as Taguchi's orthogonal array. Fisher's orthogonal array focused on calculating factor-by-factor contributions of variability in product characteristics. Taguchi's orthogonal array focused on control factors that engineers had means to affect. While environmental condition or noise factors affect product characteristics there were no means to control them.

A typical Taguchi's orthogonal array (L_8) for seven two-level factors is shown in Table 10. L refers to Latin square and the subscript eight refers to the number of runs. From the experiment design, the number of times each level (A or B), appears in each column is equal. A and B each appear four times in every column. Such a design ensures that each factor has an equal opportunity to influence the results (Roy 2001). Taguchi's orthogonal array requires only eight experimental runs as compared to 128 runs if a full factorial design was used. In orthogonal array design, having a resolution of three (e.g., Taguchi's orthogonal array) means that the main factors are confounded with interaction effects. Such designs are generally accepted and considered useful for the purpose of screening the effects of factors (NIST/SEMATECH 2012).

Table 10. Taguchi's L_8 Orthogonal Array (after Taguchi, Chowdhury, and Wu 2005)

	Factors						
Run	**A**	**B**	**C**	**D**	**E**	**F**	**G**
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

Taguchi's orthogonal array is well established and validated by many. Sedghi et al. (2014) used both a full factorial design and the Taguchi method for estimation of the in vitro optimum intrinsic phytase activity of rye, wheat, and barley. The results using both methods were comparable. However, the Taguchi method required significantly lesser number of runs.

Using Taguchi's orthogonal array resolves the issue of having two-level and three-level factors by allowing a mixed array design. In addition, the required number of runs is minimized to a reasonable 36 runs.

One of the advantages of using a DOE is that many statistical analysis software packages are now able to perform DOE automatically thus saving much time and effort. The software used in this thesis is JMP Pro 11, mainly due to prior experience of the author in using JMP Pro 11, and availability of the software package on the NPS campus. Table 11 shows Taguchi's orthogonal array design (L_{36}) for 10 two-level factors and three three-level factors in JMP Pro 11. The factors and corresponding data labels are provided in Table 12 for reference.

Table 11. Taguchi's L_{36} Orthogonal Array Design in JMP Pro 11

Rn	Sspd	Srdt	Rspd	Xspd	Etim	Cang	Espd	Wrdt	W30	W120	Drng	Erng	Nint
1	Slow	Yes	Slow	Slow	Short	Less	Slow	Yes	Yes	Yes	Short	Short	1
2	Slow	Yes	Slow	Slow	Short	Less	Slow	Yes	Yes	Yes	Med	Med	2
3	Slow	Yes	Slow	Slow	Short	Less	Slow	Yes	Yes	Yes	Long	Long	3
4	Fast	Yes	Fast	Slow	Short	Less	Fast	No	No	Yes	Short	Short	1
5	Fast	Yes	Fast	Slow	Short	Less	Fast	No	No	Yes	Med	Med	2
6	Fast	Yes	Fast	Slow	Short	Less	Fast	No	No	Yes	Long	Long	3
7	Fast	No	Slow	Fast	Short	Less	Slow	No	No	No	Short	Short	2
8	Fast	No	Slow	Fast	Short	Less	Slow	No	No	No	Med	Med	3
9	Fast	No	Slow	Fast	Short	Less	Slow	No	No	No	Long	Long	1
10	Slow	No	Fast	Slow	Long	Less	Slow	Yes	No	No	Short	Short	3
11	Slow	No	Fast	Slow	Long	Less	Slow	Yes	No	No	Med	Med	1
12	Slow	No	Fast	Slow	Long	Less	Slow	Yes	No	No	Long	Long	2
13	Fast	Yes	Fast	Fast	Short	More	Slow	Yes	Yes	No	Short	Med	3
14	Fast	Yes	Fast	Fast	Short	More	Slow	Yes	Yes	No	Med	Long	1
15	Fast	Yes	Fast	Fast	Short	More	Slow	Yes	Yes	No	Long	Short	2
16	Fast	No	Slow	Fast	Long	Less	Fast	Yes	Yes	Yes	Short	Med	3
17	Fast	No	Slow	Fast	Long	Less	Fast	Yes	Yes	Yes	Med	Long	1
18	Fast	No	Slow	Fast	Long	Less	Fast	Yes	Yes	Yes	Long	Short	2
19	Fast	No	Fast	Slow	Long	More	Slow	No	Yes	Yes	Short	Med	1
20	Fast	No	Fast	Slow	Long	More	Slow	No	Yes	Yes	Med	Long	2
21	Fast	No	Fast	Slow	Long	More	Slow	No	Yes	Yes	Long	Short	3
22	Slow	No	Fast	Fast	Short	More	Fast	Yes	No	Yes	Short	Med	2
23	Slow	No	Fast	Fast	Short	More	Fast	Yes	No	Yes	Med	Long	3
24	Slow	No	Fast	Fast	Short	More	Fast	Yes	No	Yes	Long	Short	1
25	Slow	Yes	Fast	Fast	Long	Less	Fast	No	Yes	No	Short	Long	2
26	Slow	Yes	Fast	Fast	Long	Less	Fast	No	Yes	No	Med	Short	3
27	Slow	Yes	Fast	Fast	Long	Less	Fast	No	Yes	No	Long	Med	1
28	Slow	Yes	Slow	Fast	Long	More	Slow	No	No	Yes	Short	Long	2
29	Slow	Yes	Slow	Fast	Long	More	Slow	No	No	Yes	Med	Short	3
30	Slow	Yes	Slow	Fast	Long	More	Slow	No	No	Yes	Long	Med	1
31	Fast	Yes	Slow	Slow	Long	More	Fast	Yes	No	No	Short	Long	3
32	Fast	Yes	Slow	Slow	Long	More	Fast	Yes	No	No	Med	Short	1
33	Fast	Yes	Slow	Slow	Long	More	Fast	Yes	No	No	Long	Med	2
34	Slow	No	Slow	Slow	Short	More	Fast	No	Yes	No	Short	Long	1
35	Slow	No	Slow	Slow	Short	More	Fast	No	Yes	No	Med	Short	2
36	Slow	No	Slow	Slow	Short	More	Fast	No	Yes	No	Long	Med	3

Table 12. Factors and Data Label Mapping for JMP Pro 11 DOE Setup

Factors	Label	Factors	Label
Range of detection	Drng	Exposure time	Etim
Platform speed during scan	Sspd	Coverage angle	Cang
Number of intelligence sources	Nint	Platform speed during engagement	Espd
Sensor redundancy	Srdt	Weapon redundancy	Wrdt
Platform speed on road	Rspd	Ability to withstand up to 30 mm gunfire	W30
Platform cross-country speed	Xspd	Ability to withstand one 120 mm round direct hit	W120
Range of engagement	Erng		

C. SCENARIO DEVELOPMENT

The previous section discussed the different levels associated with each factor that may influence the design of the MAD system. Each factor may affect the performance of the MAD system differently in diverse environments. While the environment is not a controllable factor, it does affect the system performance, and should be considered as noise factor(s) during design. In this section, scenarios will be discussed to illustrate the differing impact of factors in regards to the performance of the MAD system.

Morrison and Mecca (1988) categorize scenarios into four distinct types, namely, the demonstration scenario, the driving-force scenario, the system change scenario, and the slice-of-time scenario. The following descriptions of different types of scenarios are summarized from Morrison and Mecca (1988).

In the demonstration scenario, a particular end-state in the future is envisaged along with a path of determining events leading to that end-state. Correspondingly, the decisions made at each determining event influence the end-state. The decisions made at these determining events are the focus of the demonstration scenario.

In the driving-force scenario, key trends are first identified with different intensities, that is, low, medium, and high. The key trends are assumed to be constant throughout the scenario and with different intensities. Diverse versions of the future could thus be described. In this way, the driving-force scenario contrasts alternative futures with others in a similar scenario space. Certain policies may suit some of the futures but create problems in others. The driving-force scenario thus allows decision-makers to direct monitoring attention to potential problems.

The system-change scenario explores interrelationships of a set of trend and event forecasts. This scenario type differs from the demonstration and driving-force scenarios in that there is no single event that will affect the scenario or assumed driving forces.

The slice-of-time scenario takes a snapshot of a future period in time when certain conditions have progressed to a certain extent, for example, technology. A description of how stakeholders think, feel, and behave in that environment is provided. The objective is to compare the future to current state and assess if the future was more desirable, fearful or more attainable than generally thought.

In defining the operating scenarios for the MAD system, the author uses the driving-force scenario with the threats to maneuver forces as the identified key trends. The intent is to compare the design decision of the MAD system in alternative futures. In an essay on scenario planning, Peterson, Cumming, and Carpenter (2003) stated that the appropriate number of scenarios is generally considered to be three or four. Two scenarios result in narrow thinking; whereas five or more scenarios may confuse users and limit their ability to explore uncertainty (Wack 1985; Schwartz 1991; van der Heijden 1996). Consequently, the author describes three scenarios where the MAD system operates in different terrain.

The scenarios have to take into account the presence of threats to maneuver formation. The recent trend in regard to threats faced by the maneuver formation was discussed in Chapter II. The main identified threats were fixed wing aircraft, attack helicopters and UAVs/UCAVs. A rational adversary would employ forces based on the effectiveness and advantage(s) in that particular operating environment. Consequently, threat intensities may vary with different operating environments. Threat intensities refer to the number of assets deployed by the adversary to attack the maneuver formation. For the purpose of building the scenarios, threat intensity levels are mapped to three indicative states, that is, low, medium, and high. The generalized threat and intensity levels are shown in Table 13. Each scenario will have an assessed intensity for each threat. The assessed threat intensities build a reasonable scenario, which is representative of typical military missions. With better knowledge, combat experience, and data, the threat intensities could be better assessed.

Table 13. Generalized Threat and Intensity Levels

Threat	Intensity		
Fixed Wing Aircraft	Low	Med	High
Attach Helicopter	Low	Med	High
UAV/UCAV	Low	Med	High

1. Scenario One: Flat and Open

The maneuver force may need to operate in different terrain depending on which region of the world or country the need for maneuver capability is required. The first envisaged scenario has flat and open terrain. This operating environment resembles a desert. In such an operating environment, there is no relief for cover and concealment. There is also little or no foliage. Correspondingly, there are also no physical blockages thus resulting in good visibility (assuming good weather). The traveling surface is relatively level but can be "soft" at times.

Scenario One has flat and open terrain. The lack of relief or foliage means that attack helicopters are unable to leverage on the cover provided by relief or foliage for low-level maneuvers. Hence, there is no advantage in deploying attack helicopters over fixed wing aircraft to attack maneuver formations in such an operating environment. The adversary would also be concerned about attrition of air assets. Without the advantage of avoiding detection using relief and foliage, the attack helicopter is slower than fixed wing aircraft, and would present an easier target for anti-aircraft weapons. The author opines that in such a scenario the deployment of fixed wing aircraft for the attack of maneuver formations would be high while that of attack helicopters would be low. UAVs/UCAVs would be advantageous in this scenario due to the absence of flight crew, thus preventing human casualties. Being physically smaller in size, UAVs/UCAVs tend to be harder to detect. However, the payload of UCAVs may not be sufficient to neutralize a maneuver formation. UCAVs are likely to be used in moderation until more technological advances are made. Since there is no significant advantage of using air assets in this scenario, the adversary may then deploy more ground assets to counter the maneuver formation. Such inter-relationships may affect the significant of factors of MAD systems, which will be discussed later in the chapter. The summarized threat and intensity levels for scenario one are shown in Table 14.

Table 14. Threat Density for Scenario One

Threat	Intensity
Fixed Wing Aircraft	High
Attack Helicopter	Low
UAV/UCAV	Med

2. Scenario Two: Some Relief

The second envisaged scenario has some relief including hills, knolls, and winding tracks. There is also some foliage present. This operating environment resembles a sparse forest. In such an operating environment, the adversary threat could leverage on the presence of foliage and relief for cover and concealment. In addition, there may be physical blockages with regard to visibility and operation ranges of weapon(s) and sensor(s). In this scenario, the surface that the maneuver formation has to traverse upon is undulating.

The threat of fixed wing aircraft is assessed to be low in this scenario taking into account aircraft radars may not fare well when transmitting through foliage. Hence, the adversary could opt to deploy attack helicopters that could leverage on cover and concealment before launching a surprise "pop-up" attack on the maneuver formation. UAVs/UCAVs are likely to be deployed as well due to lower probability of detection. Similar to attack helicopters, UAVs/UCAVs would be able to make use of the relief and foliage for cover and concealment. In view of UCAV current payload capabilities, attack helicopters are assessed to be the threat of highest intensity. UAVs/UCAVs are assessed to be of medium intensity, as shown in Table 15. Due to attack helicopters and UAVs/UCAVs being able to leverage on the relief and foliage, the adversary is likely to deploy more air assets as compared to ground assets.

Table 15. Threat Density for Scenario Two

Threat	Intensity
Fixed Wing Aircraft	Low
Attack Helicopter	High
UAV/UCAV	Med

3. Scenario Three: Urban Built-Up Area

The third envisaged scenario is an urban built-up area. An urban built up area presents a significantly different operating environment for the maneuver force formation. The landscape comprises mainly buildings with relatively narrow roads. Maneuverability may be limited for GCVs. Field of view is severely limited due to physical blockages by buildings. The traveling surface is flat and mostly in the form of hard surfaces, such as, paved roads.

In such a scenario where the maneuver formation is restricted in maneuverability, the adversary is likely to deploy fast moving air assets as opposed to main battle tanks, which may be restricted in maneuverability in an urban built-up area. Fixed wing aircraft are fast but if a building is blocking the line of attack, the aircraft has to make another pass, reducing the probability of engagement. On the other hand, attack helicopters have the ability to hover and make slight positional adjustments to get a clear line of attack. Attack helicopters would be most lethal in such a scenario; however, the adversary would also be mindful of casualties. Attack helicopters are vulnerable to more threats in urban areas; for example, rocket propelled grenades typically have limited range to target attack helicopters, but the presence of buildings extends the range of rocket propelled grenades. UAVs/UCAVs could serve a similar function with many UAVs/UCAVs now able to hover. The author opines that attack helicopters would be deployed in moderation while UAVs/UCAVs would be deployed in higher intensities due to the absence of flight crew onboard. The threat and intensity levels for scenario three are shown in Table 16.

Table 16. Threat Density for Scenario Three

Threat	Intensity
Fixed Wing Aircraft	Low
Attack Helicopter	Med
UAV/UCAV	High

D. NOISE FACTORS

From the three scenarios discussed, the contributing effect of the environment could be categorized into two main noise factors. The first noise factor is the presence of blockages (relief and foliage), which is a very significant factor by itself. The presence of blockages affects sensor and weapon ranges, indirectly determining the time of reaction for the maneuver formation. The time of reaction in turn leads to other considerations; for example, with less time to react, the coverage angle of the weapon may be more significant as the crew may not have sufficient time to slew the weapon system to engage the threat. The second identified noise factor is the traveling surface. Undulating or difficult terrain (e.g., soft ground and steep slopes) makes the cross-country speed of the MAD system more significant. On the other hand, easy terrain like paved roads negates the usefulness of cross-country capability. Similar to signal factors, noise levels are associated with levels. Each noise level is associated with two-levels—present or absent.

E. RESPONSE: SURVIVABILITY OF THE MANEUVER FORCE FORMATION

Much has been said about the impact of different factors on the performance of the MAD system. However, one should keep in mind the objective of having a suitable MAD system. The aim is to defend the maneuver force formation against aerial threats, thus contributing to the overall survivability of the formation. DOE requires a response in order to determine if factors are significant. Consequently, the survivability of the formation, which is also the MOM, is designated as the response of the DOE. For each run with different factor levels, there would be a corresponding response. In this way, factors of the proposed MAD system that are significant in affecting the overall survivability of the formation could be determined.

1. Methods of Assigning Significance

When dealing with systems in the conceptual stage, there is often a lack of data. In order to compare alternatives, weights may be assigned to attributes in order to facilitate comparison. The use of swing weights in multi-attribute decision-making is one method of analyzing the alternatives (Clemen and Terence 2001). This methodology involved assigning weights to attributes and normalizing them for a better comparison. However, the weights assigned can be subjective. In order to reduce subjectivity, the author identified the use of a general quality loss function proposed by Choi and Langford (2008) to calculate the significance of each factor objectively. The general loss function is based on Taguchi's quality loss function (Taguchi 1990).

a. Taguchi Quality Loss Function

Taguchi (1990) proposed that quality in relation to cost and loss applies not only to the manufacturer during production but also to the consumer and society as a whole. Customers who received a poor product would develop negative reactions and eventually no longer consume the product. Such consumer behavior eventually causes loss to the manufacturers in the long term. In quantifying the relationship between cost and loss, Taguchi proposed quality loss functions for three characteristics, namely, nominal-the-best, smaller-the-better, and larger-the-better. The nominal-the-best approach is used when there is an identified target point to achieve. The smaller-the-better and larger-the-better approaches are used when trying to minimize and maximize the result respectively.

Taguchi's quality loss function is a useful tool for cost-benefit analysis, for example, to decide the amount of investment to improve a product that is already within specifications before it became no longer worthwhile. Taguchi's quality loss function aims to minimize loss to the customer by improving quality and reducing performance variation of the product (Choi and Langford 2008).

b. General Quality Loss Function

Taguchi's quality loss function applies mainly to manufacturing and production. In other phases of the system lifecycle, there is difficulty in applying Taguchi's quality loss function. Consequently, Choi and Langford (2008) felt the need to develop a quality loss function that is applicable for all acquisition phases (i.e., concept and technology development, system development and demonstration, production and deployment, sustainment and disposal) of weapon systems. Building upon Taguchi's quality loss function, Choi and Langford (2008) developed a general quality loss function applicable to all systems using competing resources. The general quality loss function as defined by Choi and Langford (2008) is

$$L_n(x) = -2C_S m^n + C_S x^n (1 + m^{2n} x^{(-2n)})$$

where

L_n: Expected quality loss

x: Response of quality

C_s: proportionality constant

m: target value

n: Shape parameter for representing an acquisition phase of a weapon system ($n > 0$)

Application of the general quality loss function was demonstrated in a South Korean project to develop a plate that is applied to the skirt of a tank (Choi and Langford 2008). Using the general quality loss function, the project team was able to derive the quality loss function for each stage, baseline cost, expected quality loss for each stage, and the amount of additional investment considered acceptable to the project stakeholder should there be a need to reduce the thickness of the plate.

c. Pugh Matrix

Although the preferred method would be the use of general loss function due to the increased objectivity, the lack of data available to the author for the creation of a model necessitates the use of other methods. In view of the lack of data for rationalization of weights assignment, the author opted for a relative comparison method in using the

Pugh Matrix (Pugh 1991). This method of assigning significance uses a "better- or worse-off" comparison between factors.

The following sub-sections will discuss the pertinent features in each of the three scenarios that result in the increased or decreased significance of factors at each associated levels.

2. Assigning Response Based on Scenarios

Prior to assigning response based on the scenarios, a baseline response is generated for basis of comparison. The baseline response is based on the ideal state where both noise factors are absent. For two-level signal factors, runs having the factor results in a binary "1" state whereas not having the factor results in a "0" state. The responses for three-level signal factors follow a similar approach. It is assumed that the benefit associated with each increasing factor level still linear at this stage. Hence, three-level signal factors are assigned "0," "1," and "2" as baseline responses.

With both noise factors absent, the range of detection is expected to be optimal. Having no blockages makes sensor(s) and weapon(s) ranges most important in a "see first, shoot first, kill first" heuristic for this scenario. The further the MAD system can detect and engage, the higher the survivability of the maneuver formation.

The key advantage of being able to incorporate data from more intelligence sources is to have backup sensors when one or more sensors are ineffective (blocked). In this scenario, having additional intelligence sources may not be that useful since all the conditions are present for the sensor to operate optimally.

Since there is no relief for cover and concealment, assuming the sensor is operating optimally with good range, the threat should be detected at a further distance. With more reaction time, the coverage angle of the weapon may be less significant as the crew would have sufficient time to slew the weapon system to the target in preparation for engagement. However, the lack of relief and foliage also means that the maneuver formation has to travel at the fastest speed possible in order to reduce time exposed to the threats. Therefore, platform speed during scan and engagement would be important in the baseline scenario. During engagement, the platform is likely to move in a steady direction to facilitate engagement. This kind of movement prevents the MAD system from executing evasive movement. A short engagement time would allow the MAD system to resume evasive movement sooner and thus reduce exposure to the threat.

As discussed previously, the adversary may opt for more ground assets to engage the maneuver formation due to the lack of any obvious advantage in deploying air assets. This strategy may result in increased significance of having protection against gunfire and tank munitions, and having redundancy for critical components for sensor and weapon. In the absence of difficult terrain, cross-country ability would not provide any extra advantage to the MAD system. Table 17 shows the baseline responses (under data label R) for the signal factors.

Table 17. Baseline Response for Signal Factors

Rn	Sspd	Srdt	Rspd	Xspd	Etim	Cang	Espd	Wrdt	W30	W120	Drng	Erng	Nint	R
1	0	1	0	1	0	1	0	1	1	1	0	0	1	7
2	0	1	0	1	0	1	0	1	1	1	1	1	1	9
3	0	1	0	1	0	1	0	1	1	1	2	2	1	11
4	1	1	1	1	0	1	1	0	0	1	0	0	1	8
5	1	1	1	1	0	1	1	0	0	1	1	1	1	10
6	1	1	1	1	0	1	1	0	0	1	2	2	1	12
7	1	0	0	1	0	1	0	0	0	0	0	0	1	4
8	1	0	0	1	0	1	0	0	0	0	1	1	1	6
9	1	0	0	1	0	1	0	0	0	0	2	2	1	8
10	0	0	1	1	1	1	0	1	0	0	0	0	1	6
11	0	0	1	1	1	1	0	1	0	0	1	1	1	8
12	0	0	1	1	1	1	0	1	0	0	2	2	1	10
13	1	1	1	1	0	1	0	1	1	0	0	1	1	9
14	1	1	1	1	0	1	0	1	1	0	1	2	1	11
15	1	1	1	1	0	1	0	1	1	0	2	0	1	10
16	1	0	0	1	1	1	1	1	1	1	0	1	1	10
17	1	0	0	1	1	1	1	1	1	1	1	2	1	12
18	1	0	0	1	1	1	1	1	1	1	2	0	1	11
19	1	0	1	1	1	1	0	0	1	1	0	1	1	9
20	1	0	1	1	1	1	0	0	1	1	1	2	1	11
21	1	0	1	1	1	1	0	0	1	1	2	0	1	10
22	0	0	1	1	0	1	1	1	0	1	0	1	1	8
23	0	0	1	1	0	1	1	1	0	1	1	2	1	10
24	0	0	1	1	0	1	1	1	0	1	2	0	1	9
25	0	1	1	1	1	1	1	0	1	0	0	2	1	10
26	0	1	1	1	1	1	1	0	1	0	1	0	1	9
27	0	1	1	1	1	1	1	0	1	0	2	1	1	11
28	0	1	0	1	1	1	0	0	0	1	0	2	1	8
29	0	1	0	1	1	1	0	0	0	1	1	0	1	7
30	0	1	0	1	1	1	0	0	0	1	2	1	1	9
31	1	1	0	1	1	1	1	1	0	0	0	2	1	10
32	1	1	0	1	1	1	1	1	0	0	1	0	1	9
33	1	1	0	1	1	1	1	1	0	0	2	1	1	11
34	0	0	0	1	0	1	1	0	1	0	0	2	1	7
35	0	0	0	1	0	1	1	0	1	0	1	0	1	6
36	0	0	0	1	0	1	1	0	1	0	2	1	1	8

a. Scenario One: Open and Flat

Scenario One only has the traveling surface noise factor present and is similar to the baseline condition in that there are no blockages. Since the traveling surface can be "soft," having cross-country capability, that is, tracked vehicles, would be advantageous as tracks are able to gain more traction on "soft" traveling surfaces. The response for Scenario One is shown in Table 18.

Table 18. Response for Signal Factors in Scenario One

Rn	Sspd	Srdt	Rspd	Xspd	Etim	Cang	Espd	Wrdt	W30	W120	Drng	Erng	Nint	R
1	0	1	1	0	0	1	0	1	1	1	0	0	1	7
2	0	1	1	0	0	1	0	1	1	1	1	1	1	9
3	0	1	1	0	0	1	0	1	1	1	2	2	1	11
4	1	1	1	0	0	1	1	0	0	1	0	0	1	7
5	1	1	1	0	0	1	1	0	0	1	1	1	1	9
6	1	1	1	0	0	1	1	0	0	1	2	2	1	11
7	1	0	1	1	0	1	0	0	0	0	0	0	1	5
8	1	0	1	1	0	1	0	0	0	0	1	1	1	7
9	1	0	1	1	0	1	0	0	0	0	2	2	1	9
10	0	0	1	0	1	1	0	1	0	0	0	0	1	5
11	0	0	1	0	1	1	0	1	0	0	1	1	1	7
12	0	0	1	0	1	1	0	1	0	0	2	2	1	9
13	1	1	1	1	0	1	0	1	1	0	0	1	1	9
14	1	1	1	1	0	1	0	1	1	0	1	2	1	11
15	1	1	1	1	0	1	0	1	1	0	2	0	1	10
16	1	0	1	1	1	1	1	1	1	1	0	1	1	11
17	1	0	1	1	1	1	1	1	1	1	1	2	1	13
18	1	0	1	1	1	1	1	1	1	1	2	0	1	12
19	1	0	1	0	1	1	0	0	1	1	0	1	1	8
20	1	0	1	0	1	1	0	0	1	1	1	2	1	10
21	1	0	1	0	1	1	0	0	1	1	2	0	1	9
22	0	0	1	1	0	1	1	1	0	1	0	1	1	8
23	0	0	1	1	0	1	1	1	0	1	1	2	1	10
24	0	0	1	1	0	1	1	1	0	1	2	0	1	9
25	0	1	1	1	1	1	1	0	1	0	0	2	1	10
26	0	1	1	1	1	1	1	0	1	0	1	0	1	9
27	0	1	1	1	1	1	1	0	1	0	2	1	1	11
28	0	1	1	1	1	1	0	0	0	1	0	2	1	9
29	0	1	1	1	1	1	0	0	0	1	1	0	1	8
30	0	1	1	1	1	1	0	0	0	1	2	1	1	10
31	1	1	1	0	1	1	1	1	0	0	0	2	1	10
32	1	1	1	0	1	1	1	1	0	0	1	0	1	9
33	1	1	1	0	1	1	1	1	0	0	2	1	1	11
34	0	0	1	0	0	1	1	0	1	0	0	2	1	7
35	0	0	1	0	0	1	1	0	1	0	1	0	1	6
36	0	0	1	0	0	1	1	0	1	0	2	1	1	8

b. Scenario Two: Some Relief

In this scenario both noise factors are present. The range of detection is expected to be less than optimal with limited ranges most of the time. The presence of blockages makes sensor(s) and weapon(s) ranges less important in this scenario as the system can only "shoot" that far provided it can "see" the threat. If the sensor range was blocked and unable to provide long-range detection but the weapon is able to have a clear line of attack, being able to incorporate data from more intelligence sources would be very useful. Other sensors may not be blocked and would be able to transmit the threat information to the MAD system for engagement. Even if there were blockages in the line of attack from the weapon to the threat, early warning would allow for more reaction time to engage the threat.

Reduced detection ranges translate to shorter reaction time. Consequently, the coverage angle of the weapon may be more significant as the crew may no longer have sufficient time to slew the weapon system to the target in preparation for engagement. The presence of relief and foliage also means that the maneuver formation now has some form of cover from the threat. Therefore, platform speed during scan and engagement would be less important than in the absence of relief and foliage. During engagement, the platform would likely need to slow down or even stop to maintain a clear line of attack. This kind of movement prevents the MAD system from executing evasive movement or being under cover. A short engagement time would allow the MAD system to resume evasive movement sooner and thus reduce exposure to the threat.

With the attack helicopters having an advantage in “pop-up” attacks, the adversary may opt for less ground assets to engage the maneuver formation. This strategy may result in reduced probability of being engaged by gunfire and tank munitions. Having redundancy for critical components for sensor and weapon may be less important than in the case of Scenario One.

In this scenario, the surface that must be traversed is undulating. Having cross-country capability would be advantageous when encountering difficult terrain. The response for Scenario Two is shown in Table 19.

Table 19. Response for Signal Factors in Scenario Two

Rn	Sspd	Srdt	Rspd	Xspd	Etim	Cang	Espd	Wrdt	W30	W120	Drng	Erng	Nint	R
1	1	1	1	0	0	0	1	1	1	1	0	0	1	8
2	1	1	1	0	0	0	1	1	1	1	1	1	2	11
3	1	1	1	0	0	0	1	1	1	1	1	1	3	12
4	1	1	1	0	0	0	1	1	1	1	0	0	1	8
5	1	1	1	0	0	0	1	1	1	1	1	1	2	11
6	1	1	1	0	0	0	1	1	1	1	1	1	3	12
7	1	1	1	1	0	0	1	1	1	1	0	0	2	10
8	1	1	1	1	0	0	1	1	1	1	1	1	3	13
9	1	1	1	1	0	0	1	1	1	1	1	1	1	11
10	1	1	1	0	1	0	1	1	1	1	0	0	3	11
11	1	1	1	0	1	0	1	1	1	1	1	1	1	11
12	1	1	1	0	1	0	1	1	1	1	1	1	2	12
13	1	1	1	1	0	1	1	1	1	1	0	1	3	13
14	1	1	1	1	0	1	1	1	1	1	1	1	1	12
15	1	1	1	1	0	1	1	1	1	1	1	0	2	12
16	1	1	1	1	1	0	1	1	1	1	0	1	3	13
17	1	1	1	1	1	0	1	1	1	1	1	1	1	12
18	1	1	1	1	1	0	1	1	1	1	1	0	2	12
19	1	1	1	0	1	1	1	1	1	1	0	1	1	11
20	1	1	1	0	1	1	1	1	1	1	1	1	2	13
21	1	1	1	0	1	1	1	1	1	1	1	0	3	13
22	1	1	1	1	0	1	1	1	1	1	0	1	2	12
23	1	1	1	1	0	1	1	1	1	1	1	1	3	14
24	1	1	1	1	0	1	1	1	1	1	1	0	1	11
25	1	1	1	1	1	0	1	1	1	1	0	1	2	12
26	1	1	1	1	1	0	1	1	1	1	1	0	3	13
27	1	1	1	1	1	0	1	1	1	1	1	1	1	12
28	1	1	1	1	1	1	1	1	1	1	0	1	2	13
29	1	1	1	1	1	1	1	1	1	1	1	0	3	14
30	1	1	1	1	1	1	1	1	1	1	1	1	1	13
31	1	1	1	0	1	1	1	1	1	1	0	1	3	13
32	1	1	1	0	1	1	1	1	1	1	1	0	1	11
33	1	1	1	0	1	1	1	1	1	1	1	1	2	13
34	1	1	1	0	0	1	1	1	1	1	0	1	1	10
35	1	1	1	0	0	1	1	1	1	1	1	0	2	11
36	1	1	1	0	0	1	1	1	1	1	1	1	3	13

c. Scenario Three: Urban Built-Up Area

Scenario Three only has the blockage noise factor present. While the net effect is similar to Scenario Two in that the sensor and weapon may encounter blockages, the processes and mechanisms of blockage may differ. The blockages in Scenario Two were due to relief and foliage. In Scenario Three, the blockages are due to buildings, and the MAD system having to negotiate narrow roads. Such movement may result in 90-degree turns and significant change of field-of-view. The author opines that in this scenario, having sensor and weapon critical component redundancies, and protection against gunfire and tank munitions is more important than in Scenario Two due to the increased chances of being surprised by the adversary forces especially when turning “blind corners.” In this scenario, the surface that must be traversed is easy terrain (paved roads). Therefore, cross-country ability would not provide any extra advantage to the MAD system. The response for Scenario Three is shown in Table 20.

Table 20. Response for Signal Factors in Scenario Three

Rn	Sspd	Srdt	Rspd	Xspd	Etim	Cang	Espd	Wrdt	W30	W120	Drng	Erng	Nint	R
1	1	1	0	1	0	0	1	1	1	1	0	0	1	8
2	1	1	0	1	0	0	1	1	1	1	1	1	2	11
3	1	1	0	1	0	0	1	1	1	1	1	1	3	12
4	1	1	1	1	0	0	1	0	0	1	0	0	1	7
5	1	1	1	1	0	0	1	0	0	1	1	1	2	10
6	1	1	1	1	0	0	1	0	0	1	1	1	3	11
7	1	0	0	1	0	0	1	0	0	0	0	0	2	5
8	1	0	0	1	0	0	1	0	0	0	1	1	3	8
9	1	0	0	1	0	0	1	0	0	0	1	1	1	6
10	1	0	1	1	1	0	1	1	0	0	0	0	3	9
11	1	0	1	1	1	0	1	1	0	0	1	1	1	9
12	1	0	1	1	1	0	1	1	0	0	1	1	2	10
13	1	1	1	1	0	1	1	1	1	0	0	1	3	12
14	1	1	1	1	0	1	1	1	1	0	1	1	1	11
15	1	1	1	1	0	1	1	1	1	0	1	0	2	11
16	1	0	0	1	1	0	1	1	1	1	0	1	3	11
17	1	0	0	1	1	0	1	1	1	1	1	1	1	10
18	1	0	0	1	1	0	1	1	1	1	1	0	2	10
19	1	0	1	1	1	1	1	0	1	1	0	1	1	10
20	1	0	1	1	1	1	1	0	1	1	1	1	2	12
21	1	0	1	1	1	1	1	0	1	1	1	0	3	12
22	1	0	1	1	0	1	1	1	0	1	0	1	2	10
23	1	0	1	1	0	1	1	1	0	1	1	1	3	12
24	1	0	1	1	0	1	1	1	0	1	1	0	1	9
25	1	1	1	1	1	0	1	0	1	0	0	1	2	10
26	1	1	1	1	1	0	1	0	1	0	1	0	3	11
27	1	1	1	1	1	0	1	0	1	0	1	1	1	10
28	1	1	0	1	1	1	1	0	0	1	0	1	2	10
29	1	1	0	1	1	1	1	0	0	1	1	0	3	11
30	1	1	0	1	1	1	1	0	0	1	1	1	1	10
31	1	1	0	1	1	1	1	1	0	0	0	1	3	11
32	1	1	0	1	1	1	1	1	0	0	1	0	1	9
33	1	1	0	1	1	1	1	1	0	0	1	1	2	11
34	1	0	0	1	0	1	1	0	1	0	0	1	1	7
35	1	0	0	1	0	1	1	0	1	0	1	0	2	8
36	1	0	0	1	0	1	1	0	1	0	1	1	3	10

F. CONDUCTING THE DOE

With responses assigned, the DOE could now be conducted using JMP 11 Pro statistical software. The DOE in JMP 11 Pro requires responses in all combinations of the noise factors. For this thesis, two two-level noise factors were determined, hence a total of four combinations are possible. The responses of the signal factors for baseline condition and the three scenarios correspond to all possible combinations for the noise factors. In the baseline condition, both noise factors are absent. For Scenario One, only the traveling surface noise factor is present. The reverse is true in Scenario Three where only the blockage noise factor is present. In Scenario Two, both noise factors are present. Consequently, the responses for baseline and the three scenarios are input into JMP 11 Pro as shown in Figure 29 via a screen capture.

	Sspd	Srdt	Rspd	Xspd	Etim	Cang	Espd	Wrdt	W30	W120	Drng	Erng	Nint	Pattern	−−	−+	+−	++	Mean	SN Ratio
1	Slow	Yes	Slow	Slow	Short	Less	Slow	Yes	Yes	Yes	Short	Short	1	−−−−−−−−−−−−−	7	7	8	8	7.5	17.443
2	Slow	Yes	Slow	Slow	Short	Less	Slow	Yes	Yes	Yes	Med	Med	2	−−−−−−−−−−000	9	9	11	11	10	19.869
3	Slow	Yes	Slow	Slow	Short	Less	Slow	Yes	Yes	Yes	Long	Long	3	−−−−−−−−−−+++	11	11	12	12	11.5	21.189
4	Fast	Yes	Fast	Slow	Short	Less	Fast	No	No	Yes	Short	Short	1	+−+−−−+++−−−−	8	7	7	8	7.5	17.443
5	Fast	Yes	Fast	Slow	Short	Less	Fast	No	No	Yes	Med	Med	2	+−+−−−+++−000	10	9	10	11	10	19.934
6	Fast	Yes	Fast	Slow	Short	Less	Fast	No	No	Yes	Long	Long	3	+−+−−−+++−+++	12	11	11	12	11.5	21.189
7	Fast	No	Slow	Fast	Short	Less	Slow	No	No	No	Short	Short	2	++−+−−−+++−−0	4	5	5	10	6	14.187
8	Fast	No	Slow	Fast	Short	Less	Slow	No	No	No	Med	Med	3	++−+−−−+++00+	6	7	8	13	8.5	17.586
9	Fast	No	Slow	Fast	Short	Less	Slow	No	No	No	Long	Long	1	++−+−−−+++++−	8	9	6	11	8.5	17.957
10	Slow	No	Fast	Slow	Long	Less	Slow	Yes	No	No	Short	Short	3	−++−+−−−++−−+	6	5	9	11	7.75	16.556
11	Slow	No	Fast	Slow	Long	Less	Slow	Yes	No	No	Med	Med	1	−++−+−−−++00−	8	7	9	11	8.75	18.489
12	Slow	No	Fast	Slow	Long	Less	Slow	Yes	No	No	Long	Long	2	−++−+−−−++++0	10	9	10	12	10.25	20.077
13	Fast	Yes	Fast	Fast	Short	More	Slow	Yes	Yes	No	Short	Med	3	+−++−+−−−+−0+	9	9	12	13	10.75	20.274
14	Fast	Yes	Fast	Fast	Short	More	Slow	Yes	Yes	No	Med	Long	1	+−++−+−−−+0+−	11	11	11	12	11.25	21.004
15	Fast	Yes	Fast	Fast	Short	More	Slow	Yes	Yes	No	Long	Short	2	+−++−+−−−++−0	10	10	11	12	10.75	20.554
16	Fast	No	Slow	Fast	Long	Less	Fast	Yes	Yes	Yes	Short	Med	3	++−++−+−−−−0+	10	11	11	13	11.25	20.908
17	Fast	No	Slow	Fast	Long	Less	Fast	Yes	Yes	Yes	Med	Long	1	++−++−+−−−0+−	12	13	10	12	11.75	21.277
18	Fast	No	Slow	Fast	Long	Less	Fast	Yes	Yes	Yes	Long	Short	2	++−++−+−−−+−0	11	12	10	12	11.25	20.948
19	Fast	No	Fast	Slow	Long	More	Slow	No	Yes	Yes	Short	Med	1	+++−++−+−−−0−	9	8	10	11	9.5	19.370
20	Fast	No	Fast	Slow	Long	More	Slow	No	Yes	Yes	Med	Long	2	+++−++−+−−0+0	11	10	12	13	11.5	21.089
21	Fast	No	Fast	Slow	Long	More	Slow	No	Yes	Yes	Long	Short	3	+++−++−+−−+−+	10	9	12	13	11	20.554
22	Slow	No	Fast	Fast	Short	More	Fast	Yes	No	Yes	Short	Med	2	−+++−++−+−−00	8	8	10	12	9.5	19.190
23	Slow	No	Fast	Fast	Short	More	Fast	Yes	No	Yes	Med	Long	3	−+++−++−+−0++	10	10	12	14	11.5	20.962
24	Slow	No	Fast	Fast	Short	More	Fast	Yes	No	Yes	Long	Short	1	−+++−++−+−+−−	9	9	9	11	9.5	19.459
25	Slow	Yes	Fast	Fast	Long	Less	Fast	No	Yes	No	Short	Long	2	−−+++−++−+−+0	10	10	10	12	10.5	20.345
26	Slow	Yes	Fast	Fast	Long	Less	Fast	No	Yes	No	Med	Short	3	−−+++−++−+0−+	9	9	11	13	10.5	20.124
27	Slow	Yes	Fast	Fast	Long	Less	Fast	No	Yes	No	Long	Med	1	−−+++−++−++0−	11	11	10	12	11	20.773
28	Slow	Yes	Slow	Fast	Long	More	Slow	No	No	Yes	Short	Long	2	−−−+++−++−−+0	8	9	10	13	10	19.597
29	Slow	Yes	Slow	Fast	Long	More	Slow	No	No	Yes	Med	Short	3	−−−+++−++−0−+	7	8	11	14	10	19.083
30	Slow	Yes	Slow	Fast	Long	More	Slow	No	No	Yes	Long	Med	1	−−−+++−++−+0−	9	10	10	13	10.5	20.192
31	Fast	Yes	Slow	Slow	Long	More	Fast	Yes	No	No	Short	Long	3	+−−−+++−++−++	10	10	11	13	11	20.682
32	Fast	Yes	Slow	Slow	Long	More	Fast	Yes	No	No	Med	Short	1	+−−−+++−++0−−	9	9	9	11	9.5	19.459
33	Fast	Yes	Slow	Slow	Long	More	Fast	Yes	No	No	Long	Med	2	+−−−+++−+++00	11	11	11	13	11.5	21.147
34	Slow	No	Slow	Slow	Short	More	Fast	No	Yes	No	Short	Long	1	−+−−−+++−+−+−	7	7	7	10	7.75	17.494
35	Slow	No	Slow	Slow	Short	More	Fast	No	Yes	No	Med	Short	2	−+−−−+++−+0−0	6	6	8	11	7.75	17.019
36	Slow	No	Slow	Slow	Short	More	Fast	No	Yes	No	Long	Med	3	−+−−−+++−++0+	8	8	10	13	9.75	19.284

Figure 29. Screen Capture of DOE Setup from JMP 11 Pro

This chapter illustrated the use of DOE for expeditious assessment of the various factors that may affect the design of the MAD system. Taguchi's orthogonal array design was selected due to the ability to provide results comparable to a full factorial design while requiring significantly less experimental runs. In the building of scenarios, different operating environments representative of typical military missions were considered. These scenarios represent noise factors that could not be controlled by the designer or engineer but affected the performance of the MAD system. A DOE requires signal factors, noise factors and responses. In lieu of availability of combat data, response was assigned to each experimental run using a "better- or worse-off" comparison. The responses were then input into JMP 11 Pro statistical software for the conduct of DOE. The presentation and analysis of results are covered in Chapter V.

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V. RESULTS AND ANALYSIS

Chapter IV discussed the rationale of using a DOE for assessing the factors that may affect the design of the MAD system. The requisite components for a DOE comprise signal factors, noise factors and responses. The use of MOMs and MOPs as signal factors, building of scenarios representative of typical military missions to distill noise factors, and assigning of significance to each experimental runs as responses were diligently discussed. The setup for DOE was thus complete and executed using JMP Pro 11 statistical analysis software. The results of the DOE are presented and discussed in this chapter.

A. RESULTS

JMP 11 Pro statistical analysis software using the least squares fitting technique generates the results of the DOE automatically. The least squares fitting technique is commonly used in linear regression (Weisstein 2015). Figure 30 shows the actual versus predicted plot for the signal-to-noise ratio. In statistics, the R^2 coefficient is a measure of the closeness of fit between actual and predicted data points. R^2 values range from zero to unity; unity represents a perfect fit. For the plot in Figure 30, the R^2 value is 0.99, which means that the fit between actual and predicted data points is close.

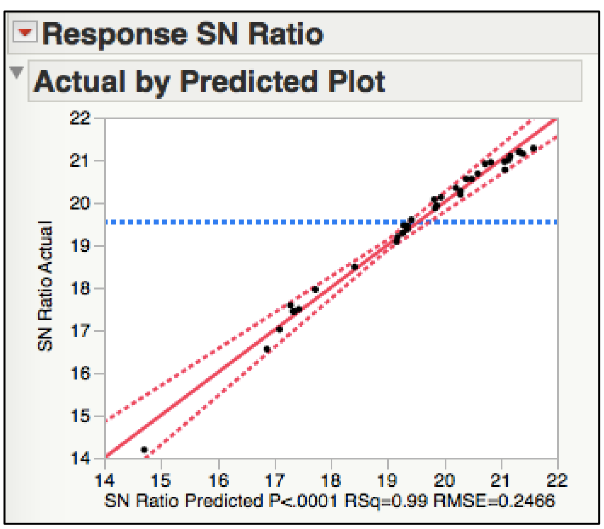

Figure 30. Actual by Predicted Plot for Signal-to-Noise Ratio

JMP 11 Pro also generates the scaled estimates for each factor at each associated level. Ten two-level factors and three three-level factors result in 29 terms, as shown in Figure 31. Using a 95% confidence level, any t-value less than 0.05 is generally considered to be significant (marked with an asterisk in Figure 31). Most terms were significant, with the exception of having two intelligences sources, which had a t-value of 0.6927. The top three significant terms were identified as short detection and engagement ranges followed by long detection range.

Scaled Estimates

Nominal factors expanded to all levels

Term	Scaled Estimate	Std Error	t Ratio	Prob>|t|
Intercept	19.52013	0.041092	475.04	<.0001*
Erng[Short]	-0.950615	0.058113	-16.36	<.0001*
Drng[Short]	-0.895545	0.058113	-15.41	<.0001*
Drng[Long]	0.7572745	0.058113	13.03	<.0001*
Etim[Long]	0.5175916	0.041092	12.60	<.0001*
Etim[Short]	-0.517592	0.041092	-12.60	<.0001*
Erng[Long]	0.7188796	0.058113	12.37	<.0001*
Srdt[No]	-0.496984	0.041092	-12.09	<.0001*
Srdt[Yes]	0.4969841	0.041092	12.09	<.0001*
W120[No]	-0.463457	0.041092	-11.28	<.0001*
W120[Yes]	0.4634571	0.041092	11.28	<.0001*
W30[No]	-0.453526	0.041092	-11.04	<.0001*
W30[Yes]	0.4535261	0.041092	11.04	<.0001*
Wrdt[No]	-0.451889	0.041092	-11.00	<.0001*
Wrdt[Yes]	0.4518891	0.041092	11.00	<.0001*
Espd[Fast]	0.3490798	0.041092	8.50	<.0001*
Espd[Slow]	-0.34908	0.041092	-8.50	<.0001*
Rspd[Fast]	0.3350762	0.041092	8.15	<.0001*
Rspd[Slow]	-0.335076	0.041092	-8.15	<.0001*
Cang[Less]	-0.2811	0.041092	-6.84	<.0001*
Cang[More]	0.2810997	0.041092	6.84	<.0001*
Nint[3]	0.3462365	0.058113	5.96	<.0001*
Sspd[Fast]	0.233843	0.041092	5.69	<.0001*
Sspd[Slow]	-0.233843	0.041092	-5.69	<.0001*
Nint[1]	-0.322918	0.058113	-5.56	<.0001*
Xspd[Fast]	0.1703902	0.041092	4.15	0.0005*
Xspd[Slow]	-0.17039	0.041092	-4.15	0.0005*
Erng[Med]	0.2317356	0.058113	3.99	0.0008*
Drng[Med]	0.1382708	0.058113	2.38	0.0280*
Nint[2]	-0.023318	0.058113	-0.40	0.6927

Figure 31. Scaled Estimates from JMP 11 Pro

B. ANALYSIS

The factors included in the DOE were specifically selected in consideration of a MAD system. It is thus unsurprising to see that most of the terms are significant. The intent of the DOE is more to compare the comparative level of significance amongst the significant factors. The top three significant terms were identified as having short detection and engagement ranges followed by having long detection range. The author opines that the identification of these three terms as most significant is reasonable. It is critical for MAD systems to at minimum have short detection and engagement ranges in order to be functional. Long detection range can result in longer reaction times, which can in turn lead to better preparation for the incoming threat. With the additional amount of reaction time, better tactics can be deployed; for example, MAD systems can be better positioned to create a "kill box" for the incoming threat.

Even without the use of combat data, there are parallels that can be drawn from the DOE results with real world trends. Following the detection and engagement ranges, the exposure time is the next most significant factor. The type of weapon system with the shortest exposure time is an FNF system. It is thus no surprise that FNF systems, most commonly in the form of infrared seeking missiles, are predominant amongst current existing MAD systems in the world.

Another example is the factor of having all round coverage weapon system, i.e., vertical-launched weapon system. Based on the DOE results, this factor does not fall within the top ten significant factors. It would seem from an operator's point of view that having a vertical-launched system would be advantageous over an oblique-launched weapon system as missiles can possibly be fired even before lock-on. However, a quick survey of existing mobile air defense systems reveals that weapon systems for MAD largely remain oblique-launched (e.g., the Stormer, Crotale (NG), SPYDER-Short Range, and Avenger). Recent air defense systems that have moved to vertical-launched modules (e.g., SPYDER-Medium Range, Aster 30 Surface-to-Air Medium Range Platform/Terrain, and S350 Vityaz) are mainly medium to long-ranged air defense systems of the HIMAD class, which may not be applicable to the capability needed in this thesis. It is imperative to note that the SPYDER short- and medium-range systems, similar systems with fully interoperable missiles, have the short-range version remain oblique-launched while the medium-range version is vertical-launched (Rafael 2015). Therefore, while having a vertical-launched weapon system does offer the advantage of lock-on-after-launch, the contribution of a vertical-launched weapon system toward overall survivability of the maneuver formation may be of a lesser magnitude compared to factors with higher significance, such as detection and engagement ranges. In a real world acquisition scenario with constraints including budget and vehicle weight, having a vertical-launched system may not be the highest priority.

After the exposure time factor, the following significant factors from the results of the DOE are related to protection against ground threats: the ability to withstand up to 30 mm gunfire or one direct hit from 120 mm tank munitions, and having sensor and weapon critical component redundancy. This result illustrates the importance of protection for a MAD system against ground threats. The Avenger, currently the only MAD system in the United States, would probably not fare well in regard to these ground threat protection–related factors. Future program executive offices and program managers managing the acquisition of MAD systems should consider improving the survivability of the MAD system with incorporation of protection against ground threats and having redundant critical components for sensor and weapon. Redundancy may not necessarily be considered in the form of each MAD system as a unit, but in terms of the maneuver formation as an SOS. For example, if there are 10 MAD systems in the maneuver formation with each having one radar, there is no sensor redundancy if each MAD system is considered as a singular entity. Operating as a maneuver formation SOS, if the track information of the 10 radars is resolved into a common air picture, even if the radar of one MAD system is killed it would not affect the overall formation due to sensor redundancy in the remaining nine MAD systems.

An interesting point to note from the DOE results is the number of intelligence sources. Based on the DOE results, having one intelligence source or more than two sources is significant. However, having only two intelligence sources is not significant. The results seem to indicate that with regard to the number of intelligence sources, one should choose between single and multiple intelligence sources.

C. APPLICATION

JMP 11 Pro has a Prediction Profiler function that presents the significance of the factors graphically, as shown in Figure 32. The steepness of the predicted profile corresponds to the significance of the factor. Correspondingly, the profiles for detection engagement ranges and short and long detection ranges, which were identified as the top three significant factors, are steeper than any other factors.

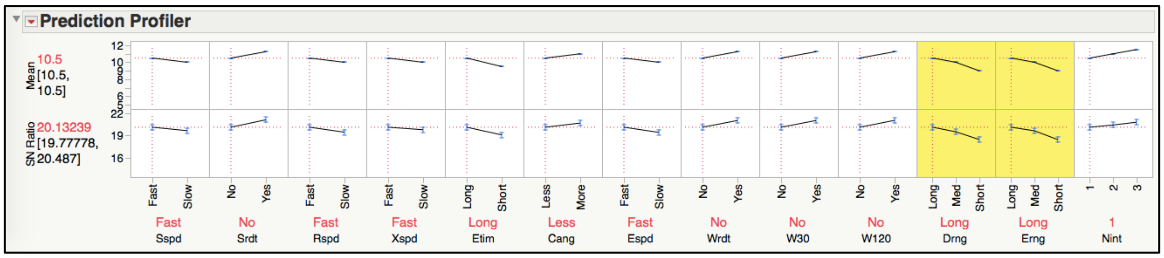

Figure 32. Prediction Profiler for Mean and Signal-to-Noise Ratio

In the DOD, it is often the case that the full capability to fulfill a need is first anticipated during project conceptualization. Toward the end of the design phase, cost-benefit analysis is conducted to determine the optimized cost-benefit point for design selection. The result of the cost-benefit analysis can result in the program having to settle on a percentage of the full capability.

There is a Desirability function in JMP 11 Pro that can aid the decision-making process in the above-mentioned situation by recommending the type of MAD system suitable for a specified desirability level. The values of desirability ranges from zero to unity. When all factors are set to the highest possible level, the value of the desirability factor is closest to unity. In Figure 33, the desirability factor is at about 0.76. At this desirability level, JMP 11 Pro automatically generates the optimized level for each factor. Hence, a MAD system having fast platform speed during scan and engagement, no sensor and weapon critical component redundancy, fast road and cross-country speed, oblique-launched weapon system, no protection again 30 mm gunfire and 120 mm tank munitions, long detection and engagement ranges, and one intelligence source is expected to perform to a desirability level of about 76.3 percent of the full capability, in comparison to a desirability level of about 81.6 percent of the full capability for two intelligence sources, and increasing to a desirability level of about 87.3 percent of the full capacity for three or more intelligence sources. The corresponding signal-to-noise ratio and mean responses are also automatically calculated as shown in Figure 33.

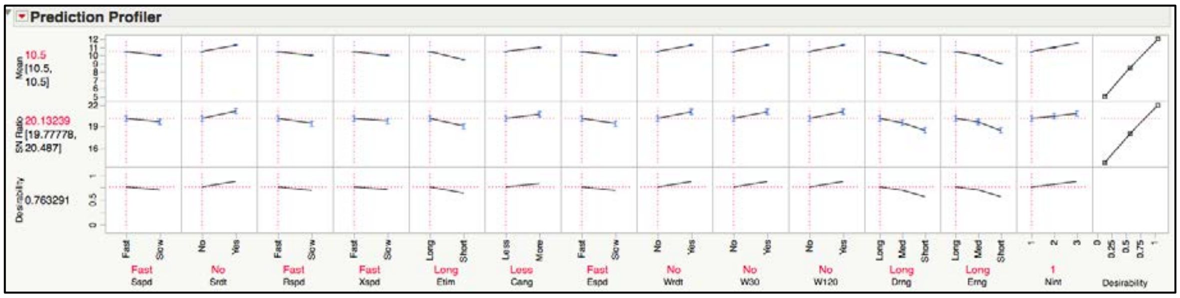

Figure 33. Prediction Profiler with Desirability Function

Overall, the results of the DOE have shown reasonable representation of real world trends. If the DOE was conducted with combat data as responses, the result should be improved with greater precision and accuracy. The author believes that the results of the DOE show sufficient realism to be useful as a tool for the acquisition of a MAD system.

VI. CONCLUSION

Acquisition of a weapon system is a complex and iterative task. This study adopted a systems engineering approach with the aim of developing an assessment framework for the acquisition of a MAD system. The systems engineering process is a systematic and holistic method of generating the required functions and components to implement the capability and operational activities needed by stakeholders. The decomposition methodology used for operational and functional analysis enables complex problems to be broken down into simpler and more manageable problems. In addition, the conduct of operational and functional analysis at an SOS level enabled better appreciation of complementary functions between the GCVs and MAD systems in the maneuver formation. The use of model-based systems engineering provides an interlinked framework that allows for iterative work while maintaining track of follow-on changes. Subsequently, MOMs and MOPs were defined to ensure overall likelihood of mission success and functional performances respectively.

The use of the DOE expedited the assessment process with regard to factors that may affect the design of the MAD system. Input factors to the DOE were mainly MOPs generated from the system engineering process. In addition, factors related to combat survivability were included. While combat survivability (encompassing the 12 concepts for reducing susceptibility and vulnerability) is well established for aircraft platforms, combat survivability design consideration for land platforms currently utilizes a few select susceptibility or vulnerability reduction concepts. The inclusion of combat survivability–related factors as inputs to the DOE ensures combat survivability is considered early in the design phase, thus preventing the need to conduct costly changes to incorporate combat survivability enhancements later on in the system lifecycle. As part of the DOE setup, the scenarios generated to represent typical military missions allowed the distillation of noise factors, that although uncontrollable affect the performance of the MAD system. The presence of blockages (e.g., relief and foliage) and traveling surface were the two noise factors determined from the scenarios. The consideration of noise factors in the DOE allowed for a more representative assessment of the performance of MAD systems in the operating environment.

The DOE results are indicative of real world trends. Based on the DOE results, having short detection and engagement ranges is most critical for MAD systems. In addition, long detection range can enhance performance. The exposure time was also identified to be a high significance factor. This result is supported by real world trends in that most existing MAD systems have an FNF system to minimize exposure time.

A. SUMMARY

A systematic and interlinked assessment framework for the acquisition of a MAD system has been developed. The use of model-based systems engineering tool and statistical analysis software is envisaged to expedite the assessment process significantly. Further validation of the framework with the use of combat data would enhance the accuracy and precision of the assessment results.

B. FURTHER RESEARCH

In Chapter IV, the initial selection of using the general loss function proposed by Choi and Langford (2008) was aimed at reducing subjectivity and increasing objectivity when assigning responses. However, the lack of data necessitated a different approach. Improvement in this area is considered key to the current framework. Future researchers could build a model using the general loss function and validate it with combat data. The validated model could then be used to calculate the responses objectively for each DOE run. Consequently, the results of DOE would be more accurate and precise.

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